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Mars Reconnaissance: Civil Engineering Advances for Human Exploration

Laurent Sibille
1Southeastern Universities Research Association (SURA)

Robert W. Moses
NASA Langley Research Center

Robert P. Mueller
NASA Kennedy Space Center

Michelle A. Viotti
Jet Propulsion Laboratory/Caltech

Michelle M. Munk
NASA Langley Research Center

See next page for additional authors

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Authors

Laurent Sibille, Robert W. Moses, Robert P. Mueller, Michelle A. Viotti, Michelle M. Munk, Paul J. van Susante, and et. al.

MARS RECONNAISSANCE: CIVIL ENGINEERING ADVANCES FOR HUMAN EXPLORATION

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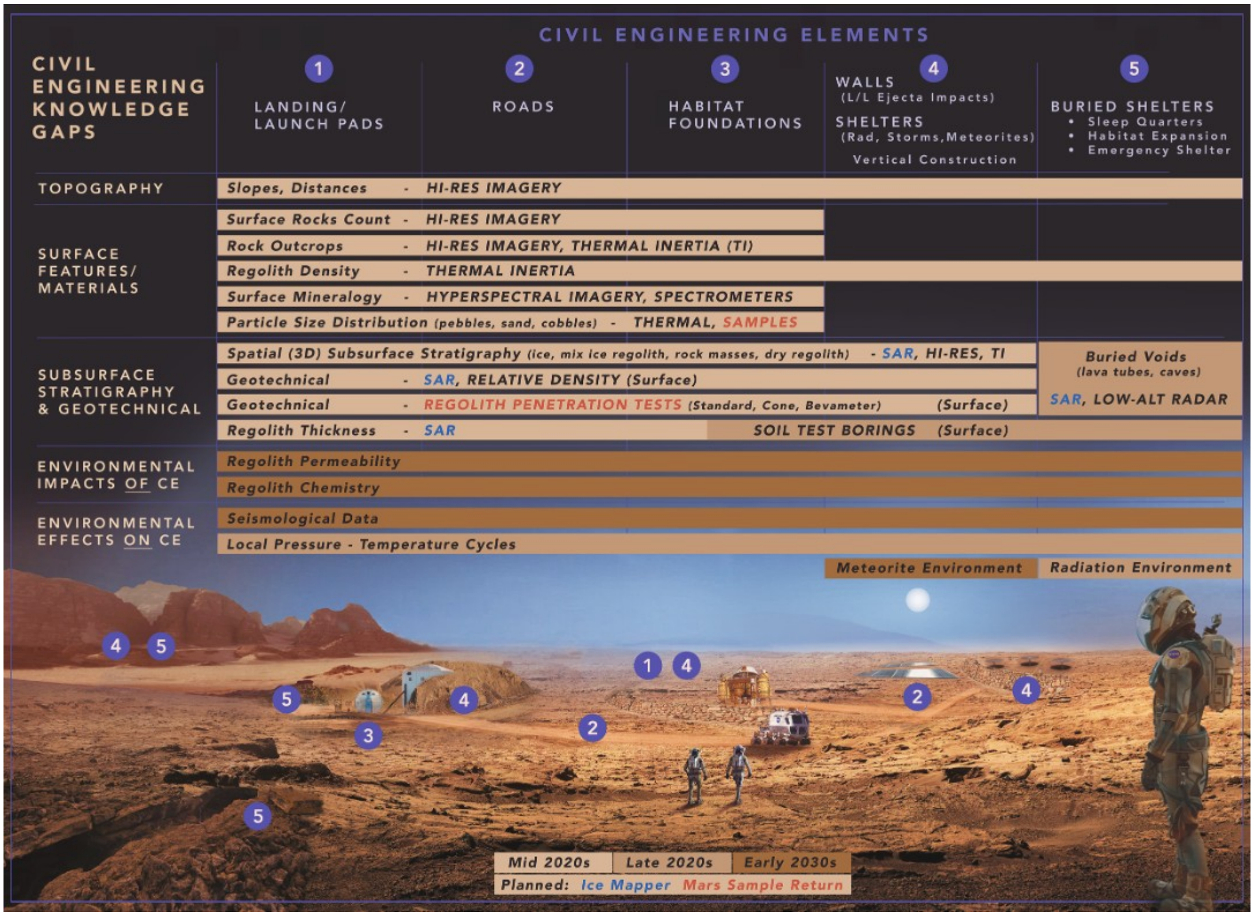
Laurent Sibille[1]; Robert W. Moses[2]; Robert P. Mueller[3]; Michelle A. Viotti[4]; Michelle M. Munk[2]; Paul J. van Susante[5]; Kris Zacny[6]; John E. Gruener[7]; Richard M. Davis[8]
[1]Southeastern Universities Research Association (SURA); [2]NASA Langley Research Center; [3]NASA Kennedy Space Center; [4]Jet Propulsion Laboratory/Caltech; [5]Michigan Technological University; [6]Honeybee Robotics, Inc.; [7]NASA Johnson Space Center; [8]NASA Headquarters;

Contact: Laurent Sibille, laurent.sibille-1@nasa.gov



SUMMARY OF CIVIL ENGINEERING ELEMENTS, KNOWLEDGE GAPS, NEEDED MEASUREMENTS,

TIMELINE, & PLANNED NEXT-DECADE MISSIONS

1.0 RATIONALE: NEXT-DECADE MARS CIVIL ENGINEERING MEASUREMENTS

Ensuring the safety of crew and cargo in future human missions to Mars is of critical importance to mission success. On Earth, we do not send people to remote, extreme environments to live for months or years without building safe shelters, landing strips, roads, and necessary infrastructure in advance. That preparation is even more critical for Mars explorers who will not have access to all of the normal and emergency resources available on our home world. To date, no campaign planning has targeted high-priority civil-engineering (CE) knowledge gaps that would significantly reduce risks and costs of human missions to Mars. While useful for initial context, data collected about Mars by past and current missions is insufficient for CE needs, particularly to ensure the first safe landings and ascents of large reusable landers. With human missions planned for Mars in the 2030s, few Mars launch opportunities remain to gain critical understandings of the Martian terrain and environment. In addition to precursor measurements identified by previous studies as risk-reducing for Mars human missions (Beaty, 2005), we place the emphasis on the critical importance of CE-enabling measurements. If strategically considered in mission formulation, high-priority civil engineering measurements that address CE knowledge gaps could be accommodated in next-decade missions at relatively low cost (e.g., either additional instruments or modifications to their requirements on the planned Mars Ice Mapper mission, the suite of Mars Sample Return spacecraft, and/or small missions and rideshares).

A primary civil engineering (CE) goal for Mars reconnaissance in the next decade is to survey (in sufficient detail) candidate Landing and Habitation Zones within 100km-radius Exploration Zones (EZs) in order to characterize the terrain, surface materials, and subsurface structure for five CE support functions (see also title-page graphic) for selecting and preparing the first human landing and settlement site:

1. Landing / Launch Zone. Utilize a natural zone (e.g., basalt layer) for initial landings and then make improvements by constructing landing/launch pads and facilities using local materials and engaging in site preparation (van Susante, 2018).
2. Foundations. Understand the ability of the subsurface to support: the habitat, shelters, and tall structures (e.g., a communication tower, solar power towers, radiators, and storage tanks), the selection of a safe location given environmental factors and seasonal events, and the nature of surface materials for use, waste management, and toxicity.

3. Roads. Develop safe routes that will receive heavy traffic by crew and vehicles in the habitation zone (including between the landing/launch pad and the habitat), as well as routes that provide repeated access to science/resource regions of interest .
4. Walls and Shelters. (vertical construction). Strategically place protective walls and shelters to serve as safe havens for crew during long traverses in case of weather, meteorite shower, or radiation events. Blast protection walls can shield habitat and other critical assets from shock waves and particle ejecta from a landing / launch zone., and also may surround fission surface power (FSP) units with local regolith used as radiation shielding to reduce the distance of their deployment from crew activities.
5. Buried Shelters. Where possible, utilize natural formations such as buried lava tubes and caves as sleep quarters to limit the total exposure of crew to radiation, leverage the strength of the surrounding rock to create large pressurized enclosures with thinner shells, and expand livable and working space for an eventual sustained human presence on Mars.

In its early phases, a settlement capable of sustaining 5 crews and their traverses in the Exploration Zone will be limited in the amount of surface assets brought from Earth. Civil engineering of a Mars base using local materials for permanent constructions would potentially deliver longer longevity and more reliable structures since indigenous materials are best “adapted” to the Martian environment and its weathering cycles than imported structures. This is especially important if long periods of non-habitation occur between crewed missions; a returning crew will be able to execute repairs and maintenance in situ with local materials. Understanding site features including environmental conditions are required before site planning and development estimates can be performed. As on Earth, topography (e.g., slope) and location of hazards (e.g., soft sand or boulders) and other terrain features (e.g., bedrock and outcrops) are required. This acquisition of knowledge is paramount as a first step in the chain of decisions that leads to the construction of a settlement.

2.0 CE Objectives for Mars Reconnaissance

The first human crew to arrive on Mars will immediately be confronted with CE concerns upon landing (e.g., engine plume interactions with the surface and the bearing capability of the subsurface). The safe installation of a permanent habitat with power sources on the surface will require good understandings of the foundation underneath, as well as prevailing environmental factors (e.g., dust accumulation patterns, range of temperatures, presence of shallow subsurface ice that could liquefy under pressure, and thermal inputs from the habitat). The navigability of Martian terrain has challenged rovers over the years, and will be exacerbated during long traverses of 10s of kms by heavier crew transport vehicles enabling scientific exploration of the region. Multiple traverses over the same routes to access locales of high scientific interest will require knowledge of surface materials, the degree of their consolidation, and resulting geotechnical properties. In the short term, for early human missions, civil engineering likely centers on the construction of launch/landing pads, roads, radiation shelter, and in situ resource utilization (ISRU) support, with additional support in the long-term for human activities such as mining, in situ manufacturing, and agriculture.

In the next decade, the following CE objectives are of highest priority for the safety and success of human missions to the Martian surface:

1. Identify load-bearing sub-surfaces that would support large, heavy, reusable landers and Mars Ascent Vehicles. The largest lander delivered on the Martian surface to date, Mars rover *Curiosity* weighs 1 tonne (t); Entry, Descent, & Landing (EDL) experts estimate that the performance of current state-of-the-art EDL technologies may successfully land a 2-t spacecraft. Current reusable human-class landers in design will be of the 20-t class. The experience of multiple landings on Mars has shown that the use of active propulsion near the surface result in fast erosion of the regolith and particulate ejecta that can damage the lander itself. In 2012, the Curiosity rover suffered damage to wind sensors from plume-triggered ejecta while under hover under the Sky Crane propulsion stage (Gomez-Elvira et al., 2014). The collimation of engine plumes causes high gas impingement pressures on the regolith and bearing failure followed by explosive erosion (Mehta et al., 2013). The interactions of rocket engine gas plumes with the regolith and rock formations are the focus of extensive studies and modeling efforts for human landers and presented in another white paper by Watkins et al. to the Planetary Science Decadal Survey (Watkins et al., 2020). Some landing concepts involve clearing the overburden of a buried ice sheet or finding a surface rock outcrop as a site for first landing. Prior knowledge of the terrain, surface materials and subsurface structure of the selected landing zone will play a critically important role in its selection as a safe location to receive a large lander without inflicting damage to the spacecraft itself.

The changes inflicted to the landing zone by the resulting erosion will have consequences since it will create a new terrain upon which the crew will offload surface vehicles, supplies, and perhaps proceed to deploy a habitat if this has not been accomplished robotically on an earlier landing.

2. Identify suitable terrain for construction, trafficability, and the availability of in-situ materials as resources for construction. The use of reusable landers for cargo and crew to Mars include the capability to produce propellants on Mars and refuel return spacecraft. Mission success will rely on the execution of transporting cryogenic liquid propellants (e.g. oxygen and methane) on the Martian terrain and delivering it to the ascent vehicle. CE will play a critical role in determining the bearing strength of the natural regolith materials and designing roads and stabilized paths to be constructed from local materials. Mining activities will also play a role as the resources for construction feedstocks and making propellant and other life support consumables must be found and acquired with robotic excavators and haulers.
3. Determine, manage, and mitigate the reciprocal effects CE and the Martian environment have on each other. The extreme environment of Mars creates a unique operational environment for the first landed crew on Mars and challenges CE designs to ensure mission success. For example, Mars is a dynamic planet where seasonal weather patterns produce constant changes both in the atmosphere and on the surface. Seasonal dust storms and localized liquefaction of brines with motion of surface regolith are the result of thermal and pressure gradients throughout the tenuous atmosphere between poles and low latitudes. Poorly known seismic activity and the radiation environment without the protection of a planetary magnetic field contribute to risks that civil engineering can address by ensuring sound structures and shelters. Beyond site preparation, civil engineering involves mitigating the potential effects of CE and crew activities on the local environment. Civil engineering and construction activities will disturb the surface and subsurface of the site through excavation, earth moving, and materials processing. Examples include protection of water-ice resources from habitat wastes and reducing the effects of chemical processing operations on the natural environment that is of great interest to scientific investigations. further to create a unique operational environment of the first crew landed on Mars and challenge CE designs to ensure mission success. Site planning activities must also consider the restrictions imposed by “special regions” where access is not possible due to the potential for the existence of biological life forms.

To meet these objectives, CE knowledge gaps must be addressed by next decade missions, targeted efforts to leverage existing data, and cross-community human landing site studies.

3.0 State of Knowledge based on Mars Robotic Missions

The U.S. and European Mars exploration programs have created a sustained presence of orbital platforms for the study of the planet over many years. The totality of the surface of Mars has been mapped at different resolutions in visible and infrared imagery enabling the study of geologic history, the dynamic interactions between the atmosphere and the surface, and the seasonal changes of ice accumulations. The process of selecting landing sites for U.S. spacecraft now involves the modeling of data obtained by several orbital instruments: orbital estimates of slopes at 100 to 1 m length scales are derived from high-resolution imagery with Mars Reconnaissance Orbiter's HiRISE camera (0.3m/pixel) and Context Imager (CTX; 8m/pixel);photoclinometry, and radar returns and areal rock density in the form of cumulative fractional area (CFA) maps are derived from high-resolution imagery, thermal emission, and advanced regolith fractionation models to display both actual and estimated distributions of rocks (Golombek et al., 2017, 2020). The production of surface mineral maps with Mars Reconnaissance Orbiter's Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) instrument (Wray, 2019) has revealed a wide variety of weathered minerals locally concentrated at different periods and confirmed by surface rover investigations in several regions (Carter & Poulet, 2012). While providing initial data of interest, these capabilities are insufficient for human missions to Mars and new measurements from orbital and surface robotic missions will be required.

4.0 CE Knowledge Gaps (see also titlepage graphic)

The legacy of technology development programs for scientific investigations of Mars from orbit and on the surface has delivered both vast amounts of data and operational experience that can now support the reconnaissance phase of a human exploration program at Mars. The continued deployment of reconnaissance-focused, science-serving assets can help fill high-priority CE knowledge gaps ahead of human travel to Mars. Although terrestrial civil engineering is a centuries-old profession with a multi-faceted set of specialized disciplines, the scope of CE activities on Mars in service of early human settlement can be defined through answers to the following CE knowledge gaps, questions, and recommended measurements, which all trace to the civil-engineering reconnaissance objectives in section 1.2.

4.1 Civil Engineering Knowledge Gap 1: Topography

What measurements are sufficient to survey and to create CE-focused topographic maps for candidate Habitation Zones in order to identify and engineer safe landing zones and landing/launch pads, execute proper placement of habitats and support assets (e.g. power, communication), and assess trafficability?

The creation of high-resolution topographic maps is of prime importance as a first tool to survey the horizontal and vertical distances, slope angles, and dimensions of prominent surface features. To meet requirements for large landers, high-resolution imaging must achieve estimates of slope angles of less than 2º over a distance of 5 m for landing zones. The identification of a suitable natural site for initial landing will rely on these and other measurements to characterize bedrock masses, depth of regolith overburden, and terrain relief features at sufficient resolution to aid the selection decisions. Desired measurements include elevation at 0.3 m resolution with a spatial resolution of 5 m.

4.2 CE Knowledge Gap 2: Surface Features and Materials

What is the nature of the surface regolith and geologic features for the provision of building materials, and site planning?

The characterization of the surface from a civil engineering perspective is aimed at understanding how the local geologic formations create salient features that define the landscape and create locally available materials for construction techniques. The chemical composition and mineralogy of surface material will also play a role in the assessment of the health hazards posed by compounds like perchlorates in certain soils. Spatial resolution of surface features and materials are driven by the need to obtain estimates of boulder counts, and features that may pose hazards to traverses, landings, or the construction of foundations such as crevices, outcrops, accumulation of loose, low density material. Desired measurements include a count of rocks of sizes 20 cm and above, holes and crevices with 0.3 m characteristic length, surface mineralogy, particle size distribution, and regolith density.

4.3 CE Knowledge Gap 3: Subsurface Stratigraphy and Geotechnical Characterization

What measurements are sufficient to characterize near-surface materials and structures in order to quantify the geotechnical properties that guide above-ground construction?

The discovery of buried ice masses at mid-latitudes (Putzig & Morgan, 2019) points to the need to understand the structure of the subsurface to support many exploration activities by a crew. Scientific investigation of the formation, history, and potential of ice as a biological refuge is a prime activity. Accessibility of massive amounts of ice as a mineable resource for life support and propellant production is another major driver. The construction of foundations, landing pads, walls, roads, and access paths to underground features like lava tubes will require measurements:

- thorough knowledge of the stratigraphy of the near-subsurface to depth of 5 m and deeper as needed in the case of buried features in order to characterize the geotechnical properties of the subsurface and to understand possible seasonal impacts on soils that may involve phase changes in ice-regolith mixtures and impacts of seismic events;

- the depth and spatial dimensions of buried ice, of buried rock masses, and voids (lava tubes, caves) with a 1 m resolution in early orbital reconnaissance and 0.5 m resolution during low-altitude and surface reconnaissance;
- seasonal changes in ice accumulation or disappearance with +/- 10% error with the spatial area, known with a resolution of 1 m^2; and,
- geotechnical surface measurements including relative density of the regolith, regolith boring tests accompanied by standard penetration tests, or cone penetrometer tests and bevameter testing (Zacny, 2012.) Drilling systems can also be used for ground truthing geotechnical properties of material. Drilling power and penetration rates can be converted into the so called specific drilling energy, which in turn relates to material strength, such as compressive strength (Zacny, 2013.)

4.4 CE Knowledge Gap 4: Civil Engineering Impacts on Martian Environment

What impacts does civil engineering have on the Martian environment?

The potential effects of civil engineering activities on the environment fall under the role of environmental engineering. To understand how construction may affect the environment, the Martian environment must be characterized as it plays a critical role in defining construction requirements at a given locale. Knowledge of the chemical composition and physical characteristics of the regolith will guide decisions about control measures for waste products from the habitat and from materials processing involved in ISRU and construction, as well as the protection of water supply. Desired measurements include the permeability of the regolith, the relative density and chemical and mineral composition of the regolith. Planetary protection measures may have to be taken to be in compliance with existing protocols.

4.5 CE Knowledge Gap 5: Mars Environmental Effects on Civil Engineering

What effects does the Martian environment have on civil engineering activities?

The Martian environment is both unique in terms of its low pressure, low-humidity atmosphere, and high-flux radiation and similarity to Earth in the existence of climate and weather patterns driven by pressure-temperature gradients and cycles, lofted dust, and wind erosion. Critical measurements also include weather patterns such as dust storms in a given region, radiation levels, meteorite frequency and characteristics, seismic events, and atmospheric cycles that change pressure and temperature. While low levels of seismic activity are expected and current long-term measurements by Insight will bring more complete knowledge, it potentially affects foundation designs and construction methods and materials. The discovery of the liquefaction of brines caused by local pressure and temperature changes indicate that such a phenomenon may occur at depth under a launch pad or a foundation and needs further understanding of these occurrences at the scale of a habitation site. The frequency and size distribution of meteorite events through the tenuous atmosphere is poorly known and better knowledge will inform us on the level of risk for construction engineering. Desired measurements include location-dependent annual variations of radiation levels, seismic, and meteorite frequency and distribution, and local surface pressure and temperature changes.

5.0 Major Opportunities for Next-Decade Breakthroughs: Mission Opportunities

5.1 Planned NASA Mars Ice Mapper Mission

The Ice Mapper Mission is of great interest from a CE perspective. The potential discovery of buried ice deposits at shallow depth will be invaluable especially if it is teamed with a high-resolution imager, thermal emission sensors, and hyperspectral spectrometers for surface minerals and the detection of surface outcrops. Despite a maximum ~18 m / pixel resolution, CRISM/MRO has underperformed in the detection of small surface outcrops due to instrument artefacts and photometric and atmospheric factors (Carter & Poulet, 2012), which limits its potential for detecting features with weak spectral signatures. Hyperspectral remote sensing is now in use on Earth for high accuracy mineral mapping. Its pairing with high-resolution imagery and thermal-emission sensing on Ice Mapper would create a powerful suite providing timely information on the topography, surface materials, and subsurface bearing capacity of the natural terrain for landings of large reusable spacecraft. The limited number of launch opportunities to Mars make this mission a prime candidate for timely preparation of the CE aspects of the first landings.

5.2 Planned Mars Sample Return Mission

The prospect of returning soil and rock samples with knowledge of their original context is very exciting for both planetary scientists and engineers involved in preparing for crew stays on the Martian surface. Soil samples will enable laboratory experiments to determine fundamental values used in geotechnical engineering to guide the design of foundations and other shallow footing construction. It is reasonable to expect that the physical condition of returned soil samples will be somewhat changed by their acquisition, transfer to the return vehicle, and the sequence of events from Mars launch to Earth landing. Laboratory measurements such as standard penetration tests, porosity, shear strength, and cohesion will rely on the recreation of in-situ conditions of the samples, which can be done with in-situ measurements by Mars Sample Return. The sample collecting rover can perform a series of regolith penetration tests (standard, cone, bevameter) around each sampling area, including using drilling as a measuring method as stated above along with an onboard hyperspectral imager. The sub-scale

MAV can also provide the opportunity to obtain low-altitude hyperspectral and hi-resolution imagery of Jezero Crater that will serve to calibrate the analysis of orbital data of the area.

5.3 Next-Decade Instrument Priorities for Civil Engineering

Hi-Resolution Imaging for Civil Engineering. Current HIRISE capabilities with photoclinometry analysis for determining slopes at scales from 1 km to 1–5 m are adequate for CE needs for current landers (Golombek et al., 2020). However, the increase in engine thrust of reusable human landers by orders of magnitude from current 1-t class science landers will likely require finer knowledge of particle and small rock (5 – 50 cm) abundances by a next-generation Hi-Res imager.

Subsurface Density Imaging (Thermal emission / Surface Sample Analysis). The practice of correlating and calibrating orbital measurements of thermal inertia such as those of TES (res. 3 km/pixel) and THEMIS (res. 100 m/pixel) with rover-based surface data on particle sizes, mineralogy, and degree of cementation will be very valuable for CE in the future. The need to derive estimates for particle size distributions, degree of cementation, subsurface density, and bearing strength, as well as rock outcrops and rock abundances for large lander arrivals would be addressed by new thermal emission detectors with improved resolution to ~5-10 m/pixel when THEMIS is no longer operational. It is important to note that such advancements will require coordination of surface geotechnical measurements by rovers and landers (Perseverance, Mars Sample Return) with new orbital detectors or low-altitude survey of thermal emission signatures to extend the usefulness of models for the evaluation at all potential landing sites.

Potential Next-Decade Small Missions & Ride Sharing for Civil Engineering. The Mars 2020 experimental helicopter *Ingenuity* may herald an era of low-altitude surveying capability that could provide sets of high-resolution data in multiple areas of knowledge for CE. Within the next decade, small missions with innovative platforms such as Langley Research Center’s Mars Electric Reusable Flyer (MERF) with hyperspectral imagers and mini-SAR could help fill the knowledge gaps between single site measurements by rovers and broad regional data from orbit. Additional existing or in-development instruments aiming at geotechnical measurements for the Martian surface should be considered as ride-sharing payloads on next-decade Mars robotic missions.

6.0 Recommendations

The deployment and build-up of large assets and complex operations on Mars relies critically on civil engineering to select locations, to assess the geotechnical properties of the surface and subsurface material, and to understand the environmental factors that affect the site seasonally. In the next decade, state-of-the-art orbital detectors at Mars and the ground truth provided by rovers and landers can generate a wealth of information that provides contextual information for CE assessments of candidate human habitation sites. The planning of the arrival of large 20-t class reusable landers with crew onboard will require knowledge of the surface materials at higher resolution and new knowledge of the subsurface to select a safe site for landing and occupation. In light of this, all orbital and surface missions to Mars in the next decade should carry out complementary measurements of increased resolution that enable high-confidence estimates of geotechnical properties and mineralogy of surface and subsurface materials, including ice.

High-priority CE recommendations for Mars Recon in the next decade include:

1. **Prioritize the Mars Ice Mapper mission's radar investigation** to provide near-surface water-ice and geotechnical profiles; **include a next-generation high-resolution imager** (high priority), **weather instruments** (high priority), **thermal emission systems**, and **hyperspectral detectors** on it or other orbital platform opportunities to discern granular and consolidated materials, natural terrain features, and environmental conditions for landing site characterization.
2. **Prioritize analysis of existing orbital datasets and correlations with surface measurements** already collected or directed in the near future with *Curiosity*, *Perseverance*, and the *Mars Sample Return* reusable lander and sample-collecting rover to create early estimates of value ranges for geotechnical properties of distinct locations.
3. **Leverage every next-decade opportunity to create correlated surface and orbital measurements of geotechnical properties of the subsurface** (e.g., Mars Sample Return and small rideshare missions including rovers, landers, and low-altitude airborne surveyors).
4. **Invest in a capability to develop civil-engineering models** from these and existing collected data and studies to assess landing and habitation sites for assured human mission success.
5. **Infuse elements of civil engineering site planning in the context of a Human Landing Site Workshops** to facilitate focused cross-community discussions of common objectives to achieve safe human landings, habitability, and related surface operations.