Running remote hands-on laboratory classes in soil mechanics

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ABSTRACT: During the Covid pandemic students were not allowed to attend laboratories in person for two years. The laboratory component of the introductory soil mechanics course was adapted by introducing exercises that students could perform in their kitchen in addition to providing data and video of the conventional laboratory classes. The paper will briefly explain how the five exercises, classification, compaction, flow, compression/consolidation and shear box were adapted for remote students. Significant components of the classification, compaction and flow experiments were conducted by students at home in their kitchens. The paper will describe these home experiments, discuss the challenges and provide reflections on the experience.

Keywords: Laboratory Classes, Remote Learning, Engineering Education

1 Introduction

The COVID pandemic resulted in lockdowns and students being unable to attend university classes. The short notice presented a major challenge for laboratory work with most courses opting to either cancel any laboratory component or to provide video demonstrations in their place. This paper discusses an alternative approach in which components of the laboratory exercises were completed at home making use of commonly available pieces of equipment and materials.

As will be discussed this resulted in a significant increase in time commitment for the teaching staff and thus the reasons for continuing to offer laboratory work in this manner need justification. There is extensive literature and debate on the value of laboratory work in engineering and various authors have tried to identify the goals and benefits. Feisel and Rosa (2005) summarised this work and identified 13 fundamental objectives. Of these five are relevant to laboratory classes in the introductory soil mechanics course that is considered here, these are: using appropriate instrumentation; identifying strengths and limitations of theoretical models; collecting, analysing and interpreting data; communicating both orally and in writing about laboratory work, and sensory awareness. In engineering education more broadly some form of experimentation using physical systems is considered essential to enhance understanding of abstract concepts, increase student engagement and to introduce professional practice and skills (Lindsay & Good, 2005), and it is often mandated by accreditation authorities. In geotechnical engineering the importance of familiarity with materials and routine procedures is often stressed, but for most civil engineering students this is less important than improved conceptual understanding and making soil mechanics "real" (Airey et al., 2012). The ability of remote laboratories and simulations to meet the learning objectives of laboratory work has been questioned, with a study by Lindsay and Good (2005) concluding that alternatives to in-person laboratory classes lead to different learning outcomes, with some learning outcomes being improved at the expense of degradation in others.

Remotely performed experiments are not new, they have been offered for many years as part of open learning/distance education courses, but the motivation has been primarily to satisfy course requirements rather than on the grounds of learning. In this approach students are generally provided with specially prepared equipment and materials to allow the experiments to be performed remotely.

This has the disadvantage that it can be costly to provide the required materials, particularly if large cohorts of students are involved.

Remotely accessed experiments, where the equipment is housed in a university laboratory, have become more common recently because of the improved access, speed and reliability of internet resources. The inability to access physical laboratories during the COVID-19 pandemic has further increased interest in remote laboratories, spurring consideration of how to adapt existing exercises to a remote mode (Bhute et al., 2021). A COVID driven success with mailed ‘at-home’ geotechnical lab kits was reported by Stypulkowski et al. (2022), who found that more than 90 % of students preferred hands-on kit activities to data-only tasks. Alternatively, the laboratory activities can be changed, for example by using videos of the experiments and quizzes, to achieve the learning objectives in some other way (García-Ros & Alhama-Manteca, 2023). Videos showing equipment and procedures of standard soil mechanics tests are widely available and a useful compilation was produced by Geoengineer.org (“n.d.”). However, videos on their own are limited in that they do not require active involvement of the learners, they are unable to provide the sensory awareness and there is no physical interaction with machines and sensors. It has also been suggested that students do not obtain an understanding of experimental limitations without the hands-on experience.

Another approach that removes the need for physical experiments is to make use of simulations and other interactive learning modules (ILMs). In geotechnical engineering education triaxial test simulators have been developed (Penumadu et al., 2000; Budhu, 2000) and ILMs have been used to supplement laboratory exercises (Jaksa, 2012). These simulations permit virtual laboratory exercises to be conducted which can be an alternative to physical experiments when equipment is unavailable because of lack of space, funds or equipment failure. Well-designed simulations can also provide a richer experience allowing students to explore more options than in a time constrained physical experiment. However, simulations also have limitations and challenges: to have a positive impact the simulation must resemble reality and be firmly grounded in rich pedagogy; the user interface must be intuitive and easy to use, so that time is spent learning the discipline concepts rather than navigation (Budhu, 2000); and these resources are time intensive to develop and have a short life due to constantly changing computer systems and software (Jaksa, 2012).

Remote laboratories that can be performed virtually have been developed in other branches of engineering and science, but they appear to be underdeveloped in civil engineering and geotechnical engineering. The nature of typical soils and the challenges of soil preparation act against remote laboratories. The only exception appears to be in centrifuge testing (El-Shamy et al., 2013) where the cost of the facility has encouraged academics to explore sharing of the equipment with students at remote sites.

The ability to adapt laboratory classes depends not only on the learning objective but also the type of activity. For example, in the soil mechanics laboratories the hands-on experience is an important part of the classification and compaction experiments. In other cases, such as consolidation and shear box the manual operation is less significant, and the task is primarily one of data collection, analysis and interpretation.

Another factor that was significant in the decision to attempt the remote laboratories was the timing. In the first year where COVID-19 restrictions were put in place the introductory soil mechanics course had been set up and timetabled as normal. This meant that all students were timetabled to take 5 laboratory classes in small groups of 10 people. A decision was made to continue with the laboratory program and as the students were prevented from attending the laboratory, for the experiments to be performed remotely. As obtaining familiarity (sensory awareness) with soil materials is one of the key learning objectives it was also decided to explore how some of the simple experiments could be performed from home without requiring any material or equipment to be provided. This paper explains the standard laboratory procedure and resources and then how these were adapted for remote learning.

In the first year with COVID restrictions staff were able to access the laboratory throughout the semester and restrictions for students eased halfway through the semester, although a significant cohort of international students experienced all the laboratory classes remotely. In the second year there was a complete lockdown, unexpectedly, shortly before the start of the semester and all staff and students were remote. As in the previous year the course had been timetabled with the small group laboratory sessions, and it was decided to repeat the remote experience from the previous year, the main difference being that all staff and students were remote for the entire semester.

2 Original Laboratory Design (Pre-Pandemic)

Before the transition to remote learning, soil mechanics laboratory sessions followed a structured format. Each semester, students completed five key experiments, each illustrating a fundamental aspect of soil behaviour. The laboratory sessions lasted two hours and were conducted in small groups, allowing students to directly engage with the equipment and materials. Each experiment follows a structured learning sequence, which has been designed to maximise the learning outcomes (Airey et al., 2012).

First, students completed pre-lab preparation, which involved reading background material, reviewing relevant theories, and completing a quiz to ensure they understood the experiment's objectives. During the hands-on session, students performed the tests under supervision, collected data, and observed soil behaviour. A key part of this process was the use of a worksheet, which helped students connect theoretical knowledge with practical observations. The worksheet provided structured guidance, prompting students to record experimental data, perform calculations, and compare results with expected outcomes. By systematically working through these steps, students were able to reinforce their understanding of soil behaviour while developing analytical skills. To complete the session, they processed their data, compared results with theoretical expectations, and discussed any discrepancies. A subset of students was assigned to write a formal report analysing the experiment and discussing its significance in engineering practice. Physical presence in the laboratory was crucial. It allowed students to handle soil samples, observe changes in texture and consistency, and operate testing equipment. The sensory aspects of laboratory work, such as feeling how moisture affects soil plasticity or how compaction changes soil density, are difficult to convey through theoretical instruction alone.

Each of the five core experiments demonstrated a different soil property and its significance in geotechnical engineering. This paper focuses on the three experiments which were modified to perform at home: soil classification; soil compaction, and permeability measurement.

The classification laboratory focused on identifying soils based on their particle size and plasticity. This was achieved using a combination of sieve analysis, the hydrometer method, Atterberg tests for liquid and plastic limit, and fall cone method for liquid limit determination. The results were used to classify two soils (SP and MH) according to the Unified Soil Classification System. To enhance the understanding of existing practice for liquid limit testing, the fall cone method was used alongside the Casagrande test. This method involved dropping a weighted cone into a prepared soil sample and measuring penetration depth, providing a more precise and repeatable determination of soil liquid limit. By comparing results from different techniques, students gained a deeper understanding of soil plasticity and how variations in testing methods affect classification outcomes.

The compaction laboratory demonstrated the relationship between moisture content and soil density. In this class, students conducted Standard and Modified Proctor tests to determine the maximum dry density of a silty clay at different moisture contents. By plotting dry density against moisture content, they could determine the optimum water content for compaction. Students physically compacted soil samples using standardized procedures and observed how moisture influences the compaction process and soil appearance.

The flow tank laboratory comprised two parts, a visual representation of groundwater movement through a dam, reinforcing students' understanding of flow nets and seepage through soil and measurement of the permeability of the sand in the flow experiment using a falling head permeameter. Only the falling head permeability experiment was modified. In the standard laboratory the permeameter test is repeated multiple times with sand at different relative densities and results analysed to produce a plot of permeability against void ratio. Since different soils exhibit widely varying permeability, students gained an understanding of how sandy soils drain quickly and of the dependence of this on soil type and density.

Additional laboratory classes in the course included oedometer and shear box testing. The oedometer test introduced fundamental concepts of soil settlement and consolidation by measuring how soil compresses under different loading conditions. The shear box test allowed students to determine soil shear strength parameters including friction angle and apparent cohesion. While these experiments played a key role in the broader curriculum, they were not modified in the remote learning transition due to their need for laboratory-grade equipment and instrumentation.

Each of these experiments reinforced the relationship between soil properties and engineering design. Moisture content, particle size, and compaction all influence the strength and stability of soil in construction projects. Through direct experimentation, students observed how external forces affect soil deformation and failure. They also learned how variability in soil properties requires careful site-specific testing in engineering projects. The next section describes how the laboratories were modified for remote learning while attempting to maintain the core educational objectives of these experiments.

3 Transition to Remote Learning

The shift to remote learning presented significant challenges for soil mechanics laboratory instruction. Geotechnical experiments rely on direct interaction with soil samples, precision instruments, and controlled testing conditions, all of which are difficult to replicate in a home environment. Without access to physical labs, the course had to be restructured to ensure that students could still engage with the material and meet learning objectives while using household materials and remote instruction. A key priority in this transition was to maintain as much of the pre-COVID framework as possible. This included keeping the same flow, procedures, and worksheets to ensure continuity and minimise disruptions. The decision to retain the worksheet provided structure to the remote experiments, but it also posed challenges, as students had to rely on their own judgment in executing tests and interpreting results as the worksheets were not updated to reflect the changes in procedure.

To ensure students remained engaged and gained meaningful experience despite working remotely, the course adopted a structured three-component approach as shown in Figure 1. The first component was home-based practical work, where students performed simplified versions of the experiments using household materials. This ensured they retained some hands-on experience even without laboratory-grade equipment. The second component was instructor-led Zoom sessions and recorded videos, which covered both the original lab-based experiment and the modified home-based versions. These interactive sessions allowed students to observe standard lab procedures while engaging in discussions and asking questions in real time. The third component was data analysis and report writing. In common with the standard process all students were required to submit their filled in worksheets for sign off that the laboratory requirements had been completed. As some modifications to the experiments had been made, but not to the worksheets, this required clear communication of expectations to the students before the online sessions finished. For the subset of students required to write up a formal report real soil datasets were provided for analysis since many students struggled to obtain reliable measurements from their home experiments. This ensured that students worked with scientifically valid data while still reflecting on their own experimental observations. By structuring each experiment within this three-component approach, students maintained a level of engagement similar to the in-person lab sessions. The worksheet remained a core element of the course, guiding students through each stage of the experiments.

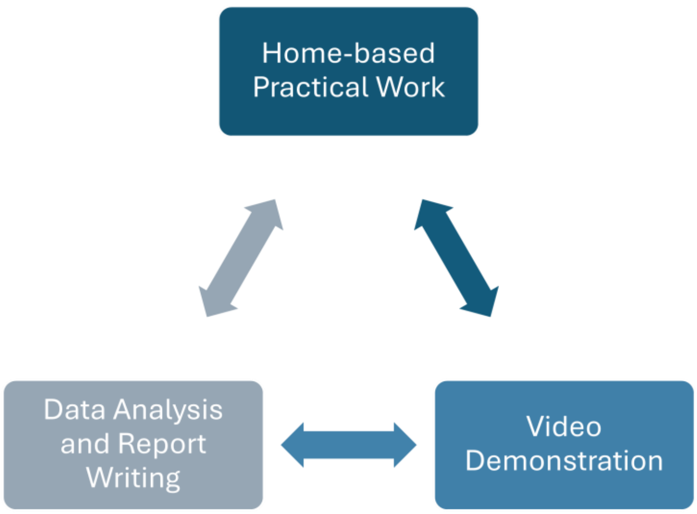

Figure 1. Three-component approach to remote lab design

The equipment and materials required for the at-home component of the experiments are listed in the Appendix. Most of these items could be purchased or be delivered from local retail shops. The main concerns were whether students would have access to a suitable balance, measuring to 0.1 g, and to a microwave. Prior to the start of the semester the possibility of using one's mobile phone as a balance was explored as there are several apps claiming the ability to measure to 0.1 g. These apps were not very stable but they were recommended as a fallback for anyone without a balance. As it turned out most students appeared to have access to accurate balances and we are unaware of anyone having to use a phone app. Microwaves were widely available and only a couple of students each year reported having to use a conventional oven.

For the classification experiment, students needed to differentiate between fine and coarse-grained materials and analyse plasticity. Various common materials were considered to determine the best substitutes for soil. Food products have the advantage of being readily available and they have a wide range of properties that can be used to illustrate soil behaviour and enhance student intuition and scale awareness (Fiegel & Derbidge, 2015). Rice flour and rice were ultimately chosen as the most suitable replacements for fine- and coarse-grained soils. Rice flour, with its finer particles, behaved somewhat similarly to silt, while rice mimicked coarse sand. Although these materials could not perfectly replicate real soil, they allowed students to observe fundamental classification concepts. As part of the particle size analysis, students used a kitchen sieve to simulate standard sieving procedures. During live Zoom sessions, the instructor demonstrated sieving rice flour through a standard stack of sieves and performing a hydrometer test, again using the rice flour, and made the results available to the students to complete the worksheets. The worksheet guided students through drawing a grading curve using their own rice and rice flour mixtures. While this was intended to be a straightforward exercise, many students struggled with the inclusion of the at home sieving step due to a lack of understanding of the classification process. It was initially planned to conduct a hydrometer sedimentation test at home and a crude hydrometer was constructed out of readily available equipment, but it was decided not to use this as it was considered too difficult for students to construct and to take any meaningful measurements. The students writing a report were provided with pre-recorded data from sieving and hydrometer tests of a silty sand. In their reports, they were required to compare their rice flour results with real soil test data from the instructional videos, but very few critically engaged with this comparison.

The second part of classification experiment involved testing for plasticity. A rough approximation of the liquid limit (60%) for rice flour was provided for sample preparation. Students mixed the rice flour and water which was to be placed in a small cup or similar sized container. A fall cone test was then performed using a custom-built cone penetrometer. A comparison between the standard laboratory cone penetrometer tip and the home-made version is shown in Figure 2. Students constructed the device using easily accessible materials, including a plastic cup, a pencil, Blu Tack, and a piping bag tip with an approximately 30-degree cone angle. The device was weighted to match the standard 80 g mass of a laboratory penetrometer. By dropping the weighted penetrometer into the sample, students could roughly measure the penetration depth after which they had to take a small sample for moisture content measurement. This used the microwave method as this provided a faster means of removing water from the rice flour samples, though it required careful monitoring to avoid overheating. Leaving the samples in the microwave for too long or using excessive power resulted in charring of the rice flour, which

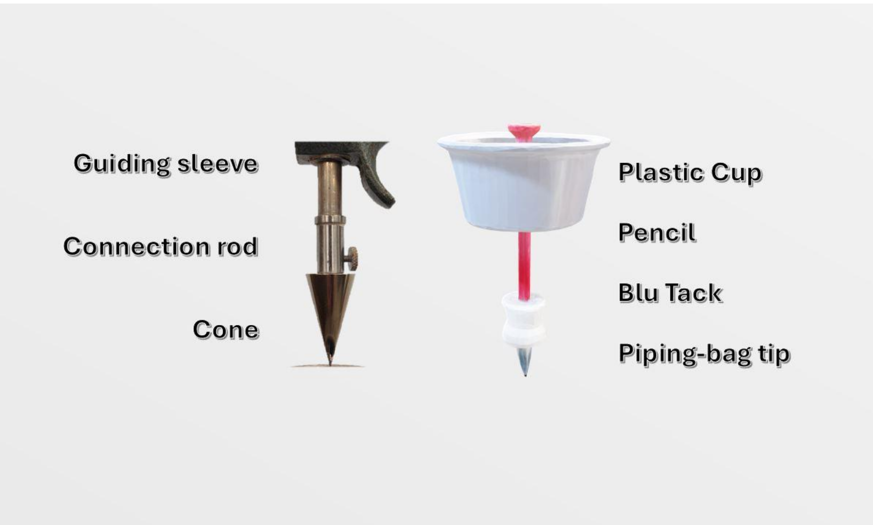

Figure 2. A comparison between a standard cone penetrometer and a home-made cone penetrometer

affected the accuracy of the measurement. To mitigate this risk, students were instructed to use short heating intervals and observe the changes in sample mass to ensure proper drying. The students also found that using too much rice flour did not allow drying out, whereas too little rice flour resulted in unreliable measurements. A second point for the moisture content, penetration graph was then required to estimate the liquid limit, taken to occur at 20 mm penetration. If the penetration in the first test was < 20 mm the students were asked to add water and if it was > 20 mm to add more rice flour, remix and repeat the experiment. The final stage was to roll out the rice flour to form a 3 mm diameter thread to estimate the plastic limit. However, because commonly available rice flour was predominantly coarse silt sized, students struggled to form the standard 3 mm diameter thread revealing the rice flour to be non-plastic. While the homemade setup lacked the precision of the laboratory cone penetrometer, it effectively demonstrated the principles and procedures behind the liquid and plastic limit determinations. Despite its challenges, this exercise still helped students understand the broader definition of soil plasticity.This approach reinforced key concepts by allowing students to observe the relationship between moisture content and soil strength, despite the constraints of working at home. Additionally, students could compare their results with video demonstrations of the laboratory fall cone test, ensuring they still developed an understanding of the method and its practical significance in soil classification.

For the compaction experiment, students compacted rice flour inside small containers, measuring the change in volume before and after compaction. Rice flour has a specific gravity of approximately 1.45 and milled rice flour has a loose bulk density in the range 0.69–0.91 g cm^{-3} (Chandra & Samsher, 2013), similar to that of other fine-grained minerals. A significant issue arose from the assumption that all students would have access to a coffee cup or a similarly sturdy container. However, some students, particularly international students, did not have access to a suitable container as they were under quarantine, and many students used containers that were too flimsy to sustain strong compaction, making it difficult to apply much force. Where students had access to soil from a garden (not topsoil), they were encouraged to perform the compaction test with real soil rather than rice flour. Rather surprisingly very few students chose this option. For students using rice flour, moisture contents of 20%, 40%, 60% and 80% were suggested as suitable target values for mixing prior to compaction, and post compaction a small moisture content sample was taken for drying in the microwave. Unlike standard laboratory Proctor tests, where a rammer is used to apply controlled compaction energy, students relied on pressing or tapping motions, which introduced variability in their results. Nevertheless, despite the poor equipment and limited compaction most students obtained reasonable dry density versus moisture content responses enabling an optimum moisture content to be estimated as the response approached the zero air voids line. To ensure consistency in data analysis, students were provided with real soil compaction data to use in their reports.

For the permeability experiment, students constructed a falling head permeameter using a clear plastic water bottle with drainage at the bottom created by punching small holes in the bottle. A thin layer of rice was placed to act as a filter followed by a layer of rice flour. The mass and height of the rice flour were measured, together with the bottle diameter to enable the density and void ratio of the rice flour to be calculated. The bottle was then filled up with water and the water level measured over time. As it took about 60 minutes for the water level to drop other components of the laboratory were then conducted. This setup preserved the fundamental principle of the falling head test, allowing students to visualise how permeability functions. While waiting a flow tank demonstration was provided via Zoom. The instructor guided students through a live session, showing how the manometer readings change with position, and ink was injected to show live the flow lines, which the students had to trace out onto a diagram of the flow tank in their worksheets. Manometer readings were read out to the students, and students used this information to create a flow net, reinforcing their understanding of groundwater flow concepts.

The other two core experiments, consolidation with oedometer and shear box testing, were deemed impractical to replicate with simple household equipment, especially when students overseas struggled to find equipment such as coffee cups. As a result, students were shown video demonstrations of the standard laboratory procedures, with instructors providing detailed explanations of the process and expected outcomes. Values of measurements from previous years were provided for students to fill in the worksheets and perform the required data analysis and interpretation. In addition to the equipment and instrumentation challenges the decision to use video was dictated by the need to follow the existing procedures detailed in the worksheet and the pre-lab material, even though alternative instructional methods could have been considered.

Table 1 presents a concise comparison of each laboratory in its original and remote formats and indicates the extent to which the five targeted learning outcomes were achieved. The previously mentioned five learning outcomes adopted from Feisel & Rosa (2005) are: (1) instrumentation; (2) recognising limits of theory; (3) data collection/analysis; (4) communication; (5) sensory awareness.

Table 1. Key differences between in-person and remote laboratories and their learning outcomes

Experiment	Delivery mode	Core activity	Learning outcomes achieved	Learning outcomes compromised
Soil classification	In-person	Sieve & hydrometer tests; fall-cone & plastic/liquid limits with two real soils	• Instrumentation • Data collection/analysis • Sensory awareness	• Instrumentation (precision)
	Remote	Kitchen sieve, rice/rice-flour grading; student made fall-cone; measure moisture content; video hydrometer data	• Data collection/analysis (partial) • Communication (worksheet/report) • Sensory awareness (partial)	
Compaction (Proctor)	In-person	Standard & Modified Proctor hammering; density/moisture curve	• Instrumentation • Theory vs. data • Sensory awareness	• Compaction energy effect • Sensory awareness (partial)
	Remote	Hand-compacting rice-flour mixes in coffee cup; density plot	• Concept of moisture–density relationship • Data interpretation	
Permeability & Flow	In-person	Falling-head test on sand at 3 densities; live flow-tank manometer grid	• Instrumentation • Theory vs. data • Sensory awareness	• Influence of density on flow
	Remote	Falling-head in bottle; Zoom flow-tank demo	• Concept of Darcy's Law • Data analysis	
Consolidation & Shear box	In-person	Oedometer loading with dial gauges	• Instrumentation • Time rate analysis • Mohr-Coulomb Theory	• Instrumentation • Sensory awareness
	Remote	Video demo; supplied data for analysis	• Concept of 1D consolidation and critical state soil mechanics • Data analysis	

Despite the transition to remote learning, the worksheet and structured framework were retained as part of the learning process. This decision ensured continuity in student engagement by providing a structured approach to data collection and analysis. However, keeping the worksheet also introduced challenges. In an in-person lab, students could seek clarification from instructors and peers, but in a remote setting, they had to work independently, which made troubleshooting more difficult. While alternative assessment formats could have been considered, the decision to retain the worksheet was based on its effectiveness in guiding students through the experimental process and reinforcing key learning outcomes.

The shift to remote laboratory learning introduced new challenges but also provided insights into how geotechnical instruction can be adapted for different environments. The next section will explore how differences in the years with remote learning affected student experiences and highlight key observations from these adaptations.

4 Reflections and Lessons Learned

The transition to remote laboratory learning provided valuable insights into both the strengths and limitations of online adaptations in geotechnical engineering education. While some aspects of the course were effectively maintained, others highlighted the challenges of replacing physical experimentation with digital resources and modifications at home. The remote format still successfully developed students' data analysis skills, with improved engagement in hands-on tasks, and provided a more individualised learning experience. However, challenges arose in maintaining effective communication, managing inconsistencies in student results, and ensuring that the broader conceptual understanding was retained. The shift also placed a significantly higher workload on instructors, as every student was individually monitored. While the overall learning outcomes were maintained, the coordination of remote labs required adjustments.

The material choice was a critical issue. It needed to be widely available, to be stable in water and consistent. Various flour products were considered before choosing rice flour. Some students sourced glutinous rice flour which did not behave like soil and the fineness and hence liquid limit of the flour varied between suppliers. Overall, the rice flour performed well, but further research is recommended to investigate other alternatives for anyone considering home experiments. Using foodstuffs assists with the sensory-awareness objective identified by Feisel & Rosa (2005) and as demonstrated by Fiegel & Derbidge (2015) can provide geotechnical analogues for a range of soil behaviours.

One of the key successes was that students appeared more engaged in the hands-on portion of the experiments. In previous years, classification tests were difficult to complete within a two-hour session due to time constraints and limited equipment. In contrast, the remote version allowed students to complete their hands-on work within the same timeframe. Unlike the in-person format, where five-student groups meant that not all students actively performed tasks, the remote setup ensured that each student conducted the full experiment independently while following live Zoom instructions. Although students were technically still part of a five-person group, the dynamic changed significantly, as each individual had to fully engage in conducting the experiment on their own rather than relying on a more confident peer to lead the process. For instructors, this setup meant that every student was under closer scrutiny, eliminating passive participation but significantly increasing the workload. With every student required to demonstrate their understanding individually through the worksheet submission, instructors had more opportunities to pinpoint specific areas of confusion, but the added supervision, additional zoom meetings, email correspondence and troubleshooting made coordination far more challenging.

Although students required less time to complete the experiments as less activities were involved, more time was spent explaining the broader context and ensuring students understood why rice flour and rice were chosen as substitutes for real soil. The classification experiment required additional discussion to help students relate the home-based experiment to real soil mechanics. Since the materials used were frictional in nature, the instructor needed to explicitly highlight how their behaviour still aligned with fundamental soil mechanics principles. These discussions were included at both the beginning and end of the experiment to reinforce the learning objectives. This additional conceptual explanation ensured that students were not only engaged with the physical tasks but also understood the underlying mechanisms they were studying.

Despite these efforts, communication over Zoom presented several difficulties. As is common in virtual environments, poor audio quality and the absence of non-verbal cues made it harder for students to fully grasp instructions. Many students also chose not to turn on their cameras, making it difficult for instructors to assess engagement and detect when students were struggling. This was particularly problematic in experiments where real-time troubleshooting was essential. In a physical lab, misunderstandings could be spotted and corrected immediately, but in the remote setting, many issues only became apparent at the end when students submitted worksheets with nonsensical data. This resulted in some students having to redo parts of the experiment to obtain usable results, leading to delays and additional sessions. Additionally, without visual engagement, instructors struggled to identify moments when students needed extra clarification, leading to repeated explanations and additional time spent reinforcing instructions.

The issue of inconsistent results across the cohort was another challenge. In classification experiments, this was partially mitigated by providing standardised soil data for analysis. However, students still conducted some measurements independently, such as coarse rice particle grading, leading to further inconsistencies. Some students attempted to bypass the challenge by using previous years' soil data instead of conducting their own measurements. These cases were easy to identify, as reports were expected to compare rice flour results with real soil data from provided datasets. This emphasises the benefit of structuring assignments in a way that encourages genuine student engagement rather than reliance on past reports.

Students had mixed opinions on the laboratory classes, but generally they were more positive about the classes that used the kitchen experiments than when only videos were provided. Some students commented that they would prefer to do the exercises in the soils laboratory, but nevertheless the lab classes resulted in a better understanding of soil mechanics through providing a specific demonstration of the concepts. These exercises had an impact on the students, they were the only hands-on exercises the cohort experienced during COVID, and this was appreciated and commented on at their graduation. This mirrors the very positive response documented in Stypulkowski et al. (2022) for other at-home activities during this period.

The laboratory exercises were timetabled which is unusual for remote experiments where students are generally provided with resources and have the freedom to perform the experiments at a time of their choosing. As these changes were implemented during COVID the set times were not an issue, but if home-based experimentation is to be used then provision of clear guidelines and procedures to enable students to complete at their own convenience would be beneficial. For the laboratories that were not adapted, remotely controlled experiments could be developed. The convenience of operating equipment from home has been positively received by students in electrical engineering (López, 2021), but as noted earlier it is important for the internet platform to be simple, intuitive and easy to use. A similar approach could be explored for soil mechanics, where a hydraulic oedometer setup could be adjusted remotely, with students inputting values online and observing changes via a camera feed. While the cost of such adaptations may be too high to justify for short-term use, a virtual reality lab could provide a more accessible alternative. A VR-based system that can work on conventional flat screen could allow students to interact with simulated soil testing equipment, bridging the gap between tactile experience and theoretical understanding.

Although remote labs presented coordination challenges, they also demonstrated potential opportunities for future hybrid learning models. A combination of online pre-lab preparation, interactive remote components, and in-person experiments could provide a more flexible and comprehensive learning experience. To address communication issues, requiring cameras to be turned on during interactive sessions or incorporating more structured participation elements could help instructors better assess student engagement. Similarly, integrating virtual lab tools could enhance students' ability to visualise and interact with soil testing processes beyond video demonstrations. With these refinements, remote and hybrid labs could serve as a valuable complement to traditional geotechnical education, providing students with flexible yet effective hands-on learning opportunities.

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6 Appendix

6.1 List of Equipment involved

Material	Classification	Compaction	Permeability
Microwave or Oven	✓	✓	
Digital kitchen scales	✓	✓	✓
Kitchen measuring cups	✓	✓	✓
Kitchen sieve – the sort used for sifting flour	✓		
Mixing bowl	✓	✓	✓
Spatula	✓	✓	✓
Access to Water	✓	✓	✓
Small container to hold wet mixture (5cm diameter x 5cm tall)	✓	✓	✓
Small microwave/oven safe plastic container	✓	✓	
Oven Gloves	✓	✓	
Cone penetrometer (Pencil, piping bag tip, Blu Tack, weighted to 80g)	✓		
Ruler	✓	✓	✓
Smooth impermeable bench surface	✓	✓	✓
1 kg Rice Flour (must be rice flour, not ordinary wheat flour)	✓	✓	✓
Larger grained foodstuff (rice, dried lentils, etc.)	✓	✓	✓
Plastic water bottle (for permeability test)			✓

Authors' bios

David Airey, University of Sydney (Australia)

David Airey is a professor of Civil Engineering at the University of Sydney who specializes in experimental geomechanics. He holds undergraduate, Masters and PhD degrees from the University of Cambridge. He has made contributions to the understanding of soil testing, soil and rock behaviour, contaminant migration in soil and rock and foundation design. He currently has students exploring Intelligent Compaction, Foundation re-use, Solar farm piles, Unsaturated soil dynamics and Offshore slope stability. He has a passion for soil mechanics and its teaching and has contributed to all the international geotechnical engineering education conferences since 2008. He is currently deputy chair of TC306 and is involved with an Australia-New Zealand team providing guidance on the education and training of geotechnical engineers.

Jiale Zhu, University of Sydney (Australia)

Jiale Zhu, also known as Joey, is a post-doctoral researcher at the University of Sydney, specialising in geotechnical engineering. His research focuses on unsaturated soil liquefaction and sustainable root reinforcement for soil stability. Joey has extensive experience in teaching civil engineering and mentoring students, alongside active involvement in professional associations. He also serves as the president of the New South Wales Chinese Students and Scholars Association, organising academic and cultural events.

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