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A vacuum-refilled tensiometer for deep monitoring of in-situ pore water pressure

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Abstract. Real-time measurement of soil water pressure has been recognized as an essential part of investigating water flow in unsaturated soils. Tensiometry, amongst different measuring techniques, is a common method for direct evaluation of water pressure. However, the lower limit of measurable water pressure by a conventional tensiometer becomes even more limited by increasing its length in the vertical installation. This paper describes the development of a Vacuum-Refilled Tensiometer (VRT) for monitoring soil water pressure independent of installation depth. This is achieved by fixing the distance between pressure sensor and ceramic cup together with incorporating an ancillary vacuum-refilling assembly into its design. The assembly allows for more efficient replacement of diffused air into the ceramic cup and reservoir with water. The new tensiometer is designed to withstand both negative and positive water pressure of up to almost one bar. In addition, the response time of the tensiometer to a change in negative water pressure for its working range (≥ -80 kPa) is very quick, in the order of seconds and one minute at most. The long-term performance of the new tensiometer is evaluated through a five-month monitoring program in the laboratory, simulating cyclic wetting and drying in the field.

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1. Introduction

Tensiometers have been used in direct measurements of soil water pressure for more than a century [1,2]. They are relatively cheap and simple to use with a straightforward theory behind. All these features make them one of the most popular devices of measuring in-situ soil water pressure. The historical emergence and development of tensiometers were reviewed in [2–

4]. The working principle and operational range of tensiometers were explained in [5]. Key components in constructing a tensiometer were summarized, and a rigorous review was conducted on alternatives that can be used for each component. According to those review papers on tensiometry, measurement of soil water pressure is limited to -85 kPa. This value is increased by 10 kPa per meter length of a conventional tensiometer in a vertical alignment. It may not be a limitation if a tensiometer is installed horizontally. Nevertheless, provisions should be made for re-configuration of its components, or other methods of suction measurement need to be used.

Measurements of a tensiometer can become independent of installation depth by minimizing the distance between pressure measuring unit and porous cup.

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This type of tensiometers was introduced in [6,7], for example, in which a pressure transducer was installed just above the ceramic cup. However, once cavitation occurs in the tensiometer, no provision has been made to refill its reservoir and resume monitoring water pressure. In order to overcome this limitation for the purpose of deep, long-term monitoring of water pressure, a new type of tensiometers called advanced tensiometers was introduced [8,9]. Refilling is conducted by flushing water through water reservoir by gravitational forces due to weight of water column in the tensiometer body. However, there is no way to remove diffused air bubbles within the cup and inside the water compartment. A two-cell tensiometer was developed to measure water pressure in the vadose zone at any depth [10]. The upper water cell is a reservoir to keep the water head essentially constant in the lower one. Therefore, corrections due to a drop of water level are not needed as it may be the case for conventional tensiometers. The design of an air pocket between two cells, however, results in slow response time in the order of hours with respect to a change in water pressure. This, in fact, limits the performance of this type to quasi steady state conditions in which sudden changes in water pressure would not be expected. In other words, the tensiometer may malfunction if monitoring of water pressure during a rainfall event is required. The response time of a tensiometer becomes of great importance when it is required to establish a reliable relationship between the soil water content and matric suction for the analyses of seepage and slope stability during heavy rainfalls [11,12].

The importance of a refilling system in addition to reducing the distance between pressure sensor and tensiometer tip was emphasized in some research [3,13]. A flushable tensiometer was introduced for long-term observations of in-situ suctions [13]. Flushing is operated by a hydraulic sliding piston from the ground surface via two tubes connected to a removable socket just above the ceramic cup. Although the tensiometer can be refilled by replacing air with water, air bubbles stuck into the cup and to the internal surface of water reservoir cannot be removed easily, and the response time can therefore be significantly affected. A vacuum source would be necessary to drag occluded air from the tensiometer and make its performance more efficient. This study aims to develop a robust tensiometer equipped with a vacuum-refilling system for measuring both negative and positive soil water pressure at any depth. The paper introduces the theory behind developing omni-depth tensiometers together with laboratory measurements of the cavitation pressure in a conventional tensiometer. Design and calibration of the newly developed tensiometer are presented afterwards. Finally, the long-term performance of the new tensiometer is compared with two Conventional

Jet-fill Tensiometers (CJT) installed in a soil column and subjected to several cycles of wetting and drying.

2. Theoretical considerations

Figure 1(a) shows schematic of a CJT with the length of h (m), inserted into a soil deposit. The soil water pressure around the center of ceramic cup is u_w^{Tip} (kPa). The Bernoulli equation is used to calculate water pressure at the location of the Precision Pressure Transducer (PPT). Derivations are presented in Figure 1(a). Since there is no water flow in the tensiometer, velocity term of energy vanishes from both sides of the equation. Therefore, the total head at each point only consists of two components: the pressure head and the elevation head. If the datum is assumed at the PPT level, a pressure component equivalent to the elevation head of h (m) should be deducted from u_w^{Tip} . As a result, water pressure at the PPT level, u_w^{PPT} , becomes a function of tensiometer length or the distance between the ceramic cup and the PPT. The difference between u_w^{PPT} and u_w^{Tip} can be minimized by minimizing the distance between the pressure sensor and the ceramic cup (i.e., h).

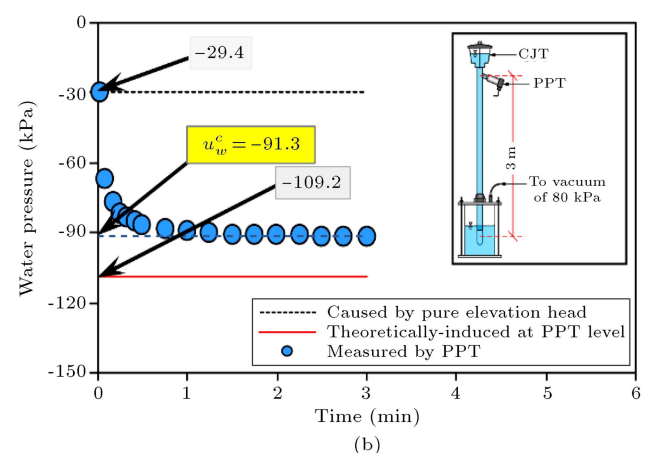
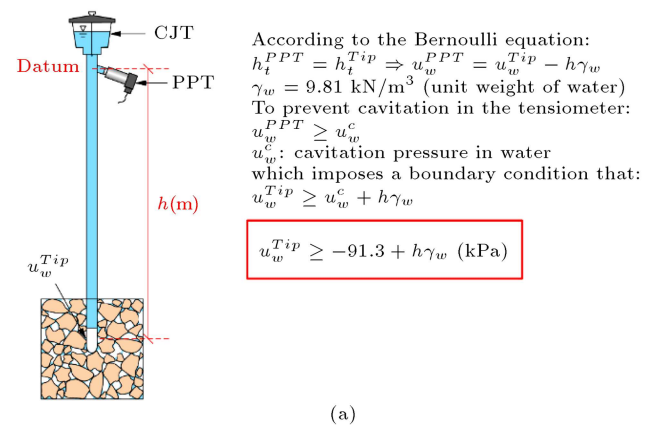


Figure 1. Effect of tensiometer length on measured negative water pressure: (a) Theoretical representation and (b) experimental results.

The cavitation pressure in tensiometers was reported as -85.3 kPa, which is a function of impurities and dissolved gases in water [5]. In addition, the existence of crevices in the ceramic and on the wall induces the cavitation points. A methodology is introduced in this study for measuring the cavitation pressure in a tensiometer in laboratory. As explained in the following paragraph, the cavitation pressure was measured as -91.3 kPa. In order to prevent cavitation in water, every point inside the tensiometer must have a pressure larger than the cavitation pressure. Since the minimum pressure happens at the PPT level (provided that the PPT is installed below the highest point of the water in the water reservoir), this point is the most critical point in terms of cavitation. In other words, if u_w^{PPT} is larger than the cavitation pressure, u_w^c , cavitation would not occur in other locations as well. If this condition, i.e., $u_w^{PPT} \geq u_w^c$, is substituted into the Bernoulli equation, a boundary condition is obtained around the ceramic cup (Figure 1(a)). The boundary condition, which is a function of the tensiometer length ($u_w^{Tip} \geq -91.3 + h\gamma_w$), states how much u_w^{Tip} could be before the occurrence of cavitation. This can be exemplified by considering a six-meter CJT. The tensiometer can only measure soil water pressure larger than -31.3 kPa. Once u_w^{Tip} drops down below this value, cavitation would be inevitable, and the tensiometer cannot function anymore. As a result, the minimum range of this tensiometer becomes limited to -31.3 kPa.

A laboratory test as depicted in the inset of Figure 1(b) was designed and conducted to measure the cavitation pressure in a conventional tensiometer. The setup includes a three-meter length CJT, a vacuum/pressure chamber, and a pressure transducer connected to the top of the tensiometer. The chamber serves as a source of vacuum or pressure applied to the tensiometer tip. Further details about it will be

presented under “Calibration setup.” The test configuration shown in Figure 1(b) aims to create a negative water pressure lower than the cavitation pressure. If a negative pressure of -80 kPa is applied to the tensiometer tip, a pressure head of -110 kPa is induced at the location of transducer based on the Bernoulli equation.

The cavitation pressure was measured according to the following procedure. The Tensiometer was filled with de-aired water. It was then inserted into the chamber and sealed to the top cap. The chamber was partially filled with de-aired water to a level that ceramic tip was totally submerged in water. The test was initiated by the first reading of the pressure transducer, which is equal to -29.4 kPa corresponding to the elevation head (Figure 1(b)). After that, a vacuum of 80 kPa was immediately applied to the chamber, which was directly transferred to the ceramic cup. Measurements of the pressure transducer were monitored and indicated against time in Figure 1(b). Results show that water pressure reached the equilibrium state in a minute, and any further decrease of pressure would not be observed. In fact, the maximum tension that can be sustained by de-aired water in the CJT is -91.3 kPa though the theoretical value is evaluated as -109.2 kPa. The latter would only be achieved if cavitation could be prevented. In summary, the cavitation pressure in a CJT filled with de-aired water was determined to be -91.3 kPa. It is noted that this value could be influenced by the saturation procedure and the existence of impurities in the system.

3. Design specifications

The new tensiometer has three main components like any other tensiometer, namely a ceramic cup, a pressure-measuring unit, and a water compartment connecting the first two components together [3,5]. Figure 2(a) shows all components of the newly developed

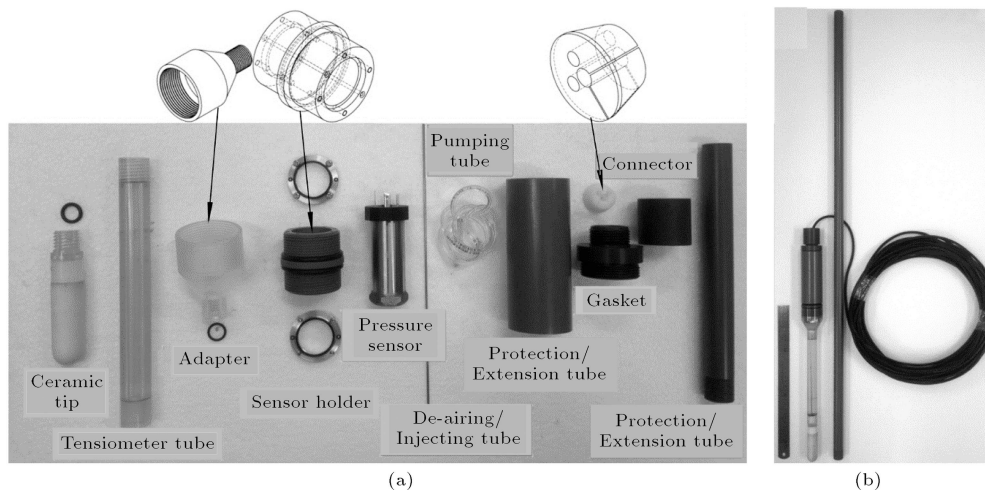


Figure 2. Design of a newly developed tensiometer: (a) All components of the sensor and (b) final assemblage.

tensiometer. A commercial 1-bar high flow ceramic cup was used as the porous interface between water inside the tensiometer and soil water. A CYH300 type pressure transducer manufactured by the Shanghai wins Co. with the measuring range of ± 100 kPa and the accuracy of $\pm 0.2\%$ FS was used as the PPT. Minor modifications were applied to the sensor body to make the strain gauge diaphragm directly exposed to water inside the reservoir and to accommodate the whole sensor inside the tensiometer body. The pressure diaphragm of the sensor penetrated 10 mm into an inverse conical-shaped adapter. This technical consideration makes the correction of pressure reading unnecessary even if a drop of 10 mm in water level from the top of water reservoir happens due to the air diffusion.

In addition to the main components, some ancillary parts were considered in the design, making the tensiometer different from conventional ones. A three-piece sensor holder was designed to accommodate the pressure transducer and refilling tubes. The sensor holder is connected from the bottom to the tensiometer tube via the inverse conical-shaped adapter and from the top to the extension section. The adapter provides more volume of water above the sensor diaphragm and, hence, helps to delay the refilling intervals. In order to fix and seal pressure transducer and refilling tubes to the holder, a combination of O-rings, nuts, and bolts were used. Sealing parts were designed to withstand both negative and positive pressure of more than one bar. Since the distance between the pressure transducer and the ceramic tip is kept essentially constant, water pressure readings are not a function of tensiometer length and, therefore, installation depth. In fact, there is no need to correct pressure readings in field as long as the constant head difference between the pressure transducer and the ceramic cup is considered in the calibration of the tensiometer. Since the distance between the pressure sensing diaphragm and the center of ceramic cup is fixed to 0.23 m, the tensiometer can ideally measure negative water pressure of up to -89 kPa based on the experimental results of Figure 1 (i.e., $91.3 - 0.23 \times 9.81 = 89.0$).

Although tensiometer readings become independent of its length by putting the pressure transducer and the ceramic cup together at a fixed distance, the tensiometer would malfunction once cavitation happens. As a result, it cannot be used and need to be left in place, especially if buried far deep that its removal would not be economical. This issue can be addressed by considering a refilling mechanism [8,13]. A combination of vacuum and injection was incorporated in the design of the tensiometer as refilling section. The former allows for the removal of diffused air bubbles from the ceramic tip and the water reservoir, while the latter permits refilling the tensiometer reservoir with water. This was achieved by inserting and sealing

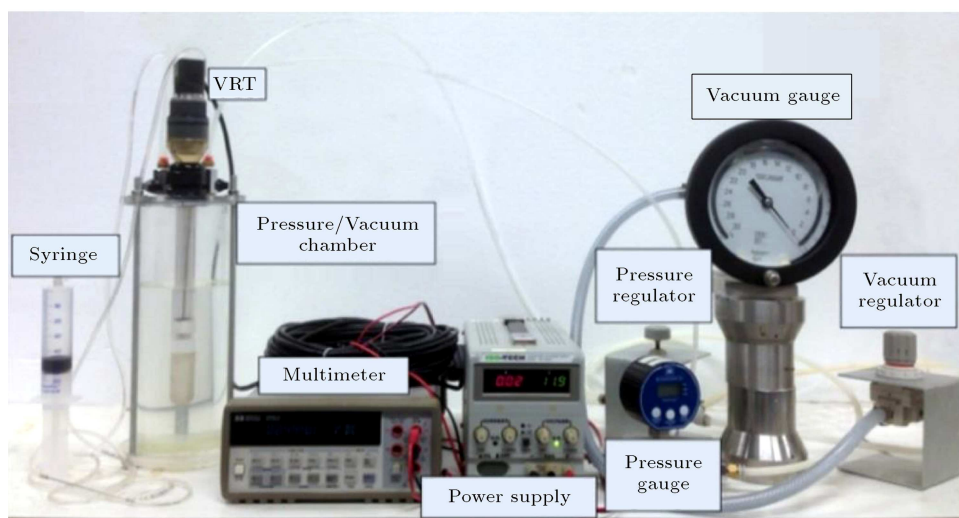
two metallic tubes into the sensor holder, one for application of vacuum and the other for injection of water (Figure 2(a)). The former was trimmed at sensor holder location, while the latter was extended to the tip of ceramic cup. Two metallic tubes can be extended by vacuum pump flexible tubes to the ground surface. Refilling process includes simultaneous sucking (from vacuum line) and injecting water (from refilling line) until no more air bubble comes out. After refilling, the two flexible refilling tubes are connected. Therefore, the hydraulic path inside the tensiometer and refilling section becomes continuous and, hence, water flow is not allowed. The hybrid mechanism of vacuum-refilling is believed to notably improve the response time due to a more efficient replacement of air bubbles with fresh de-aired water. Therefore, the new dual function mechanism considered in the current design is supposed to bring more benefit compared to the available advanced tensiometers.

An extension part was designed to accommodate the pressure sensor (electronic circuit), the transducer cable, and the two refilling tubes. Two types of commercial polyvinyl chloride (PVC) tubes with outer diameters of 22 and 48 mm can be used depending on borehole conditions. They can be extended to the required length as long as threads are provided on both ends of individual tubes. Extension tubes are considered to be robust enough to protect sensitive parts during both installation procedure and monitoring program. In fact, all exposed parts of the new tensiometer to the surrounding soils are constructed from materials (plexiglas or PVC) resistant to chemical deterioration and minor physical stresses during installation. A four-piece connector was designed and constructed to seal the extension tube on the ground surface. Therefore, possible damages to the pressure transducer, the cable, and the flexible tubes due to water and chemical leakage are prevented. Figure 2(b) indicates the final assembly of the VRT.

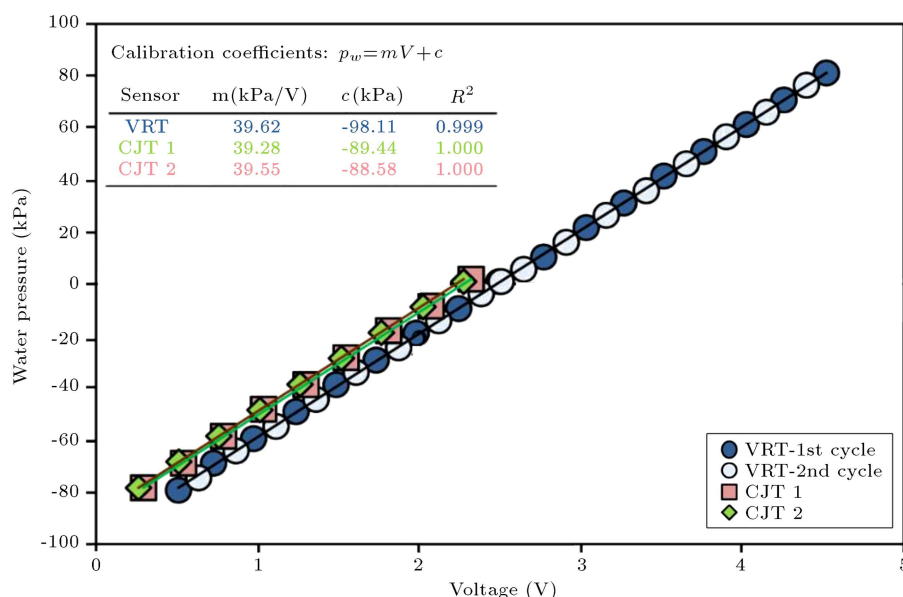
4. Calibration of the newly developed tensiometer

4.1. Calibration setup

The new tensiometer needs to be calibrated before testing in unsaturated porous media. Figure 3(a) indicates the calibration setup considered in this study. A cylindrical calibration chamber was designed and made of plexiglas. A plastic cable gland was fixed into the top cap of the calibration chamber. The diameter of the gland was considered large enough to accommodate tensiometers with a diameter of up to 25 mm. In addition, it can maintain pressure and vacuum of up to ± 100 kPa. Two valves were also installed into the top cap for independent control of vacuum and pressure. The setup also includes a power supply, a multimeter,



(a)



(b)

Figure 3. Calibration of the new sensor: (a) Experimental setup and (b) calibration curves.

and two pressure/vacuum regulators along with two pressure/vacuum gauges. The proposed calibration setup can be used for direct calibration of tensiometers. Otherwise, modification is required to consider the elevation head caused by the tensiometer length.

4.2. Calibration procedure

The calibration chamber was first filled with de-aired water about two thirds full. The VRT was then inserted into the chamber and submerged in water. It was positioned, fixed, and sealed by using the cable gland. It is noted that submerged depth (from water surface to the mid-height of the ceramic tip) was considered to calculate the applied pressure. Both negative and positive pressures were considered up to ± 80 kPa. Calibration started with the increase of

negative pressure in steps of 10 kPa until it reached -80 kPa. Vacuum was released following the same steps to zero afterwards. Pressure was then built up step by step up to a maximum of $+80$ kPa followed by a step-by-step release to zero. Vacuum and pressure were maintained for a while, and the corresponding output signal was recorded in each equalization stage. The second cycle of applying negative and positive pressure was also proceeded to check the effect of cyclic loading and unloading. In addition to the VRT, two CJTs were calibrated following the same procedure. However, they were only calibrated for negative pressure since there is no guarantee that this type of tensiometer can bear positive pressure as high as almost 1 bar. Figure 3(b) shows the results of calibration for three tensiometers. A linear response was observed for all

sensors with similar calibration factors, because similar transducers were used in all tensiometers. Moreover, hysteresis was not observed for the VRT and, hence, the response of the new tensiometer was not influenced by cycles of loading and unloading.

4.3. Response time

Two different paths namely “suction increase” and “suction decrease” were followed for measuring the response time. In “suction increase,” tensiometer was initially in equilibrium with atmospheric pressure. A predetermined negative pressure was then adjusted, but not applied to the calibration chamber yet. Timing commenced once the negative pressure was applied to the chamber and to the tensiometer accordingly. The water pressure built up in the tensiometer was monitored and recorded. An example of such measurements is shown in the inset of Figure 4 in solid blue for an applied suction of 60 kPa. The response time of the sensor to reach 60 kPa suction from zero gauge pressure is about 0.3 minutes. On the other hand, the applied suction to the chamber was immediately released to zero (atmospheric condition), and changes in water pressure were captured along “suction decrease” path. For example, response time for releasing 60 kPa suction is about 0.15 minutes as plotted in the same inset in solid pink. Of note, pressure was assumed to be in equilibrium once no further changes in the output voltage of the sensor were observed.

The above-mentioned procedure for quantifying the response time was repeated for suction values of 10, 20, 40, and 80 kPa. Results are shown in Figure 4 for both “suction increase” and “suction decrease” scenarios. Based on the results of Figure 4, the response time increases with an increase in suction. In addition, the response time for “suction increase” is consistently higher than that for “suction decrease.” The presence of a tiny bubble may delay the response during the measurement of suction going from zero to a

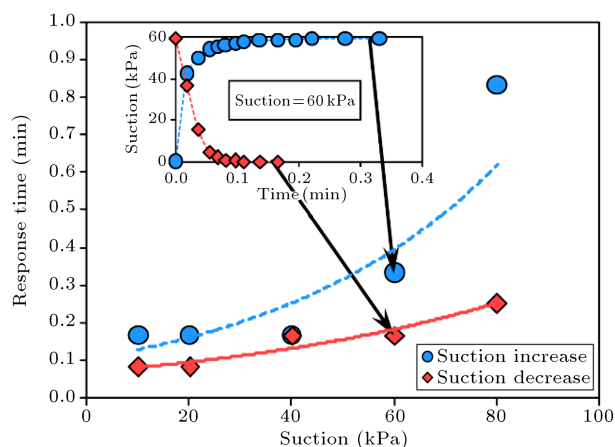


Figure 4. Response time of the tensiometer in water due to a change in negative pressure or suction.

high value. More importantly, the response time is less than a minute for the whole practical suction range of the new tensiometer. It is noted that the response time should be distinguished from the equilibrium time. The response time is an intrinsic characteristic of the tensiometer itself and is specific to the embedded pressure transducer, while the equilibrium time is influenced by many external factors. The equilibrium time is a function of the suction level [14], the unsaturated hydraulic conductivity of surrounding soils [4], the contact conditions or hydraulic continuity between the soil water and the tensiometer tip [8], the hydraulic characteristics of the porous cup [10], soil structure [15], the amount of occluded air bubbles inside the tensiometer body and its ceramic cup [5]. Therefore, changing the soil type, for example, by increasing the fine content or plasticity index, can only affect the equilibrium time by influencing soil structure and, hence, the unsaturated hydraulic conductivity. In other words, the intrinsic response time of the tensiometer may not be controlled by the surrounding soil.

5. Validation and performance of the new tensiometer

The VRT was tested inside a soil sample, and its performance during wetting and drying processes was examined and cross-checked against conventional tensiometers. The performance evaluation was conducted under controlled laboratory conditions so that the initiation of drying and/or wetting processes could be under control of the operator. However, note that the prospective aim of developing this tensiometer was for practical use in the field. Therefore, several tensiometers of this type were successfully used up to 7 m depth in a loess stratum in Xi'an to evaluate hydraulic conductivity of in-situ soils [16]. Details of sample preparation, laboratory test setup, and test procedure are explained first. Finally, results of monitoring are presented and discussed.

5.1. Sample preparation

Natural loess obtained from Xi'an, Shanxi province of China was used in this study. According to the sieve and hydrometer test analyses, the sand, silt, and clay contents of test material are 0.1%, 71.9%, and 28.0%, respectively. Having had the plastic limit and liquid limit of 19% and 38%, respectively, the soil is classified as lean clay (CL) according to the Unified Soil Classification System [17]. For the preparation of soil specimen, the required amount of oven-dried loess was sprayed with pre-determined water content. The amount of water content was 1% in excess of the in-situ water content to compensate for the water loss caused by evaporation during sample preparation. Soil-water mixture was blended thoroughly and

passed through the sieve having 2 mm aperture. The remaining part on the sieve was mixed, grounded, and sieved again. This procedure was repeated until only negligible amount remained. The mixture was cured overnight in a sealed plastic bag inside an ice chest for moisture equalization. A cylindrical soil specimen was prepared afterwards in a mold with an inner diameter of 146 mm. The specimen was statically compacted in 8 layers (each 30 mm in height) with a rate of 1 mm/min as shown in Figure 5(a). The interfaces between the layers were scratched for the sake of obtaining a more homogenous sample. Soil specimen was compacted to the target dry density and water content corresponding to the in-situ conditions. The compaction characteristics of the test material can be found in [18]. The gravimetric water content and dry density of the soil specimen after preparation were determined as 11.2% and 1250 kg/m³, respectively.

5.2. Laboratory testing procedure

A test including several cycles of wetting and drying was designed to examine the performance of the new tensiometer. In order to validate measurements of the VRT, two CJTs were included in the test program, too. The distance between the PPT sensor and centroid of the ceramic cup is 0.74 m for the CJTs. Before starting the test, all tensiometers were filled with de-aired water and put into a de-aired water bucket for a couple of days to assure saturation of the ceramic tips. Three pressure transducers incorporated into the tensiometers were connected to a PC-based data logger for monitoring and recording the measurements. The soil specimen prepared in the PVC cylindrical mold was used for installation of tensiometers. Three holes, 180 mm in depth and 19 mm in diameter, were drilled evenly in a polar array, as shown in Figure 5(a). The

diameter of holes was slightly smaller than that of tensiometers, i.e., 22 mm. Soil portion removed from drilled holes was used to prepare a slurry. The loess slurry was poured into the holes and filled them partly. The tensiometers were then pushed gently into the holes until they reached the bottom and penetrated 20 mm into the soil.

The test was started as soon as the tensiometers were inserted into the soil specimen. In order to make testing conditions similar for three tensiometers, the first wetting event was proceeded after one week from the commencement of the test. A Mariotte's bottle as shown in Figure 5(b) was used as an ancillary device to provide constant head conditions during wetting processes. After applying a constant water head on soil surface for one hour, the first wetting event was terminated. The soil column was then subjected to drying under free evaporation from the surface to the laboratory environment. Once deviation was observed in the measurements of water pressure by tensiometers, they were re-filled. The second wetting was conducted by using the same methodology, but at a reduced time of half an hour. Three more cycles of drying and wetting were followed accordingly to justify the performance of the new tensiometer during hydrological climatic changes. The importance of cyclic drying and wetting for loess properties was experimentally evaluated by comparing dynamic behavior of soil specimens, which have experienced different hydraulic histories as zero, one, and countless number of cycles [19].

5.3. Interpretation of test results and discussion

Figure 6 shows the response of three tensiometers to four cycles of wetting and drying. The variations of soil water pressure were plotted versus time in this

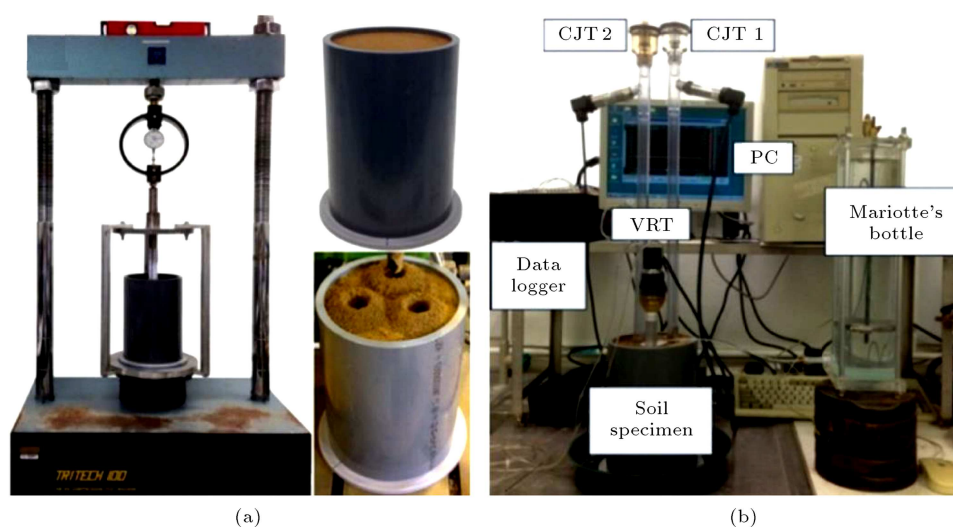


Figure 5. (a) Preparation of a cylindrical loess specimen. (b) Test setup for evaluating the performance of three tensiometers.

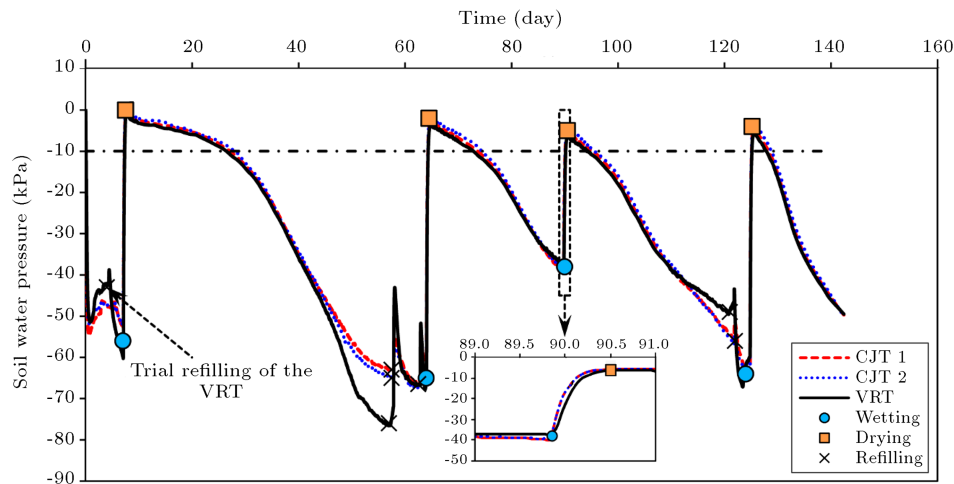


Figure 6. Response of the Vacuum-Refilled Tensiometer (VRT) along with two Conventional Jet-fill Tensiometers (CJTs) to cycles of wetting and drying.

figure. In addition, the start of wetting and drying processes was depicted by solid blue circles and solid brown squares, respectively. Cross symbol was used to indicate the refilling of tensiometers. As indicated in Figure 5, the arrangement of tensiometers from a plan view is in such a way that similar boundary conditions and interactions with the other two tensiometers can be expected for each individual tensiometer. Having assumed no horizontal water flow, one shall not ideally expect any discrepancies in measurements taken by three tensiometers. In other words, the VRT and two CJTs should yield similar values for water pressure under one-dimensional flow in the vertical direction. Therefore, the configuration of the test setup should be able to produce comparable measurements for cross-checking purpose.

The test was initiated by moving tensiometers from the water bucket to the soil column. As soon as they were pushed and placed into the drilled holes (Figure 5(a)), negative pressure started to develop until water pressure in soil and inside the tensiometers reached equilibrium. As shown in Figure 6, water pressure tended to increase afterwards due to the wetting of soil as a consequence of filling bore holes with soil slurry before installing the tensiometers. A difference of up to 3 kPa was observed between the measurements of two types of tensiometers. It was postulated that the difference arose from non-uniform distribution of water pressure caused during the installation stage. Therefore, it was decided to saturate the sample (first wetting event) to make the initial conditions similar for the three tensiometers. Although it was not required, a refilling trial was run for the VRT to check how it would respond during a refilling process (pointed with an arrow in Figure 6). Two refilling tubes were first detached and connected to a vacuum source and a water reservoir. Water was flushed afterwards until

no air came out of the vacuum tube. A rise in water pressure was observed during this stage because of the releasing of water tension applied by the soil water. After re-connecting the refilling tubes, water pressure fell sharply since water tension inside the VRT tried to reach equilibrium with that of soil water surrounding the ceramic cup. The trend of rise and fall in water pressure was also observed in the subsequent refilling processes, which is consistent with that of two CJTs as well (refer to refilling events around days 60 and 120).

As the first wetting stage started, water pressure rose dramatically in all tensiometers. The two types of tensiometer obviously have similar responses to water infiltration. The equilibrium time is not only a characteristic of the tensiometer (response time) but also a function of other factors such as soil type, degree of saturation, water pressure, and contact conditions between the ceramic and soil [5,14]. The first drying commenced afterwards with a much slower rate of pressure change compared to the wetting. Negative water pressure started to develop with a gentle slope followed by an increased rate. Results of Figure 6 clarify that water pressure decreases at an accelerated rate after water pressure drops below approximately -10 kPa. This value corresponds to the air entry value of tested material according to the measurements of pressure plate apparatus [20,21]. The increased rate of pressure change below -10 kPa can be also seen for the subsequent drying stages. A higher rate was observed for the last cycle compared to that of previous ones. This is because the whole setup was transferred to another location with a higher potential evaporation due to a maintenance operation in the laboratory.

Measurements of negative water pressure by three tensiometers are also in excellent agreement during drying process up to -50 kPa (Figure 6). Two CJTs still show close measurements afterwards, while the

VRT gives lower pressure values. Differences can be in the order of 10 kPa for an average pressure of -70 kPa. It is expected that CJTs give similar measurements since they have a similar configuration. However, the deviation in measurements of the VRT is somehow out of expectation. Jet-fill tensiometers were reported to produce reliable measurements of up to -50 kPa if they are prepared and conditioned carefully [13,22]. Although cavitation pressure is lower than -50 kPa, the diffusion of air through ceramic to the tensiometer and, hence, the creation of air bubbles inside the water reservoir cannot be prevented; even the water pressure is higher than the cavitation pressure. It is due to the fact that outer surface of the ceramic cup is exposed to a relatively dry soil environment. As a result, the concentration gradient between water inside of the cup and the air-rich soil water outside of it enhances the diffusion of air into the cup. It might be the reason that some research questioned the reliability of measurements by conventional tensiometers for water pressure less than -60 kPa [23]. The practical implication is that the in-situ conditions where extreme drying is followed by wetting may not be reliably captured if negative water pressures become less than -50 kPa. On the other hand, since this type of tensiometer is for in-depth monitoring of pore water pressure, the likelihood of the development of high suctions decreases as installation depth increases. After the refilling of all tensiometers on day 57, however, three tensiometers logged similar values, which can be considered reliable. Measurements after the refilling event were apparently a continuation of the values measured by the CJTs before the refilling. It would imply that either the values of the VRT were too low before refilling or the refilling also resulted in slight rewetting of the soil around the tensiometer cup. Further investigation is needed to clarify this issue.

The second, third, and forth wetting and drying cycles were followed afterwards. According to the results of Figure 6, responses of all tensiometers to wetting are in good agreement. The third wetting event, for example, was enlarged, as shown in the inset of Figure 6. Regarding the drying, similar measurements for three tensiometers can be also taken up to -50 kPa. It is because the second deviation happened between measurements of the VRT and CJTs during the third drying. Readings, however, converged after three tensiometers were refilled. In fact, this is a limitation of the VRT compared to a CJT; cavitation cannot be observed since the tensiometer is buried under ground. However, results of this study indicate that measurements can be in accordance with those of a CJT if all tensiometers are refilled once water pressure goes down -50 kPa. A comparison is drawn between readings of the VRT and average measurements of two CJTs in Figure 7. Results of

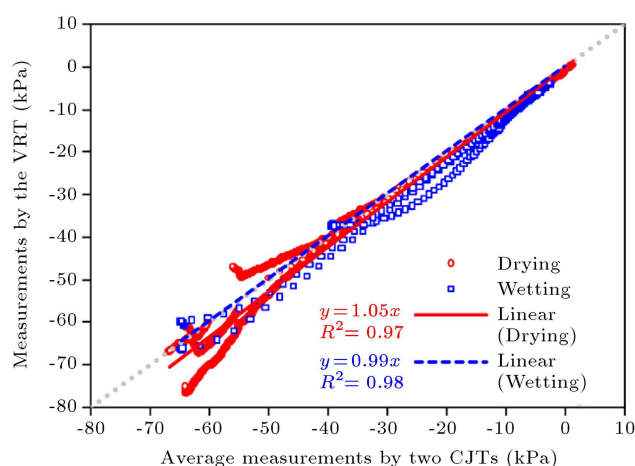


Figure 7. Comparison between measurements of two Conventional Jet-fill Tensiometers (CJTs) and those of Vacuum-Refilled Tensiometer (VRT) during drying and wetting processes.

wetting were separated from those of drying. It is noted that results of the first few days before the first wetting stage were removed from regression analysis. Based on the results of Figure 7, it seems that better agreement was achieved during wetting than drying. The reason is the discrepancy between readings of two types of tensiometer during drying periods for water pressure lower than -50 kPa. This, in fact, necessitates refilling of the tensiometers once this water pressure is reached. One possible reason is the physical process of air diffusion that cannot be stopped, even though the water pressure is above the cavitation pressure. In addition, after occurrence of the first cavitation, complete re-saturation of porous ceramic is very unlikely once suction exceeds its air entry value even though a vacuum-refilling mechanism is considered in the design.

6. Summary and conclusions

In order to study water movement in unsaturated soils, reliable evaluation of water pressure is essential. Negative water pressure can be directly measured by using a conventional tensiometer up to about -80 kPa depending on its length. This lower bound increases to -10 kPa, for example, for a tensiometer buried vertically down to 7 m underground. The paper presents the design, development, calibration, and justification of a new VRT for monitoring water pressure in field. The tensiometer can be buried underground at any depths, while the measured water pressure is not affected by the installation depth. Moreover, it can be re-operated by considering a vacuum-refilling mechanism for removing the diffused air and injecting water to the water reservoir. The specific sensor configuration helps to delay the refilling intervals as a consequence

of air diffusion. Results of calibration tests indicated that the new tensiometer had a fast response time in the order of seconds and less than one minute at most. This capability makes the instrument favorable for monitoring water pressure regime during wetting processes like water infiltration during a rainfall event. The performance of the newly developed tensiometer was cross-checked against two CJTs installed in a loess soil column. The column was subjected to four cycles of wetting and drying. It was observed that there was good agreement between measurements of the VRT and that of two CJTs for all wetting events. Readings of tensiometers were also observed to be similar during drying processes up to water pressure of -50 kPa. In order to get comparable and more reliable measurements, refilling of tensiometers is recommended for soil water pressure less than -50 kPa.

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