Long-Term In-Situ Measurement of Soil Suction in Railway Foundation Materials

Rick Vandoorne, Petrus Johannes Gräbe, and Gerhard Heymann

Abstract Volumetric water content (VWC) and matric suction vary temporally in the foundation layers of pavements and railways due to various influencing environmental factors. The resilient and permanent deformation behaviors of railway foundation materials are strongly linked to the suction within the soil, reinforcing the need for the measurement thereof. This paper reports on the installation of VWC sensors, tensiometers and fixed-matrix soil-water suction sensors in different configurations within the foundation layers of a new 26 tonne/axle railway line near Ermelo in South Africa. Local weather data was recorded using a weather station at the site. The VWC sensors and the fixed-matrix soil-water suction sensors also monitored soil layer temperature. The measurement techniques used are critically compared with regard to their ability to respond to weather events. Practical aspects pertaining to the installation procedures and maintenance required for the different techniques are also reported. It was found that tensiometers require careful consideration to ensure pore-water continuity when installed in the field. Nonetheless, tensiometers were the most reliable and accurate form of measurement in this study. The use of VWC sensors to infer suction in silica flour is a novel idea. However, this method showed limited success in this study. Fixed-matrix soil–water suction sensors provided the best long-term stability and ease of installation. However, the accuracy of these sensors requires further investigation.

Keywords Railway foundation · Soil suction · Volumetric water content · Pavement foundation

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1 Introduction

Many road and railway foundations remain in an unsaturated state for the duration of their design life. This may be due to the surfacing layers and/or the drainage systems, which prevent the complete saturation of the founding layers of roads and railways. Despite this, railways are still designed using either completely empirical techniques or mechanistic–empirical techniques based on saturated soil testing and predicted or measured in-situ moisture contents [1].

Unsaturated soil mechanics needs to be considered in order to design and understand the behavior of railway foundations from a fundamental basis. Many of the challenges hindering the adoption of unsaturated soil mechanics in geotechnical design have been addressed [2]. The soil–water retention curve (SWRC) links the soil–water potential (an energy state) to the amount of soil–water present within its pores, which can be expressed either in terms of gravimetric water content ω-SWRC, volumetric water content θ-SWRC or by the degree of saturation S_r-SWRC of the soil. Soil–water potential may be divided into osmotic and matric potential, the sum of which is termed total potential. These concepts are well explained by Toll [3] and will not be repeated here to maintain brevity. The absolute value of matric potential is termed matric suction.

The SWRC is vital for the implementation of unsaturated soil mechanics. The SWRC has interrelations with other unsaturated soil property functions such as the suction stress characteristic curve, hydraulic conductivity function and water storage function [4]. These functions dictate the mechanical and hydraulic behavior of unsaturated soil, respectively.

Toll [5] identified that in African countries many low-volume roads constructed from lateritic soils displayed better performance than could be predicted using empirical techniques based on fines content and plasticity. In fact, many of these road materials would be completely rejected based on specifications existing at that time. It was concluded that the fines in these materials allowed higher suctions to develop, which improved mechanical performance of these roads and also decreased their hydraulic conductivity, in turn reducing water ingress and maintaining the developed suctions. The importance of soil suction and fabric has thus been identified.

Figure 1 shows suctions measured on a Kiunyu gravel compacted at different water contents [6]. The lines on the plot show how the suctions changed for three of the samples as they were subjected to wetting and drying after initial compaction. A soil in the field will undergo seasonal drying and wetting cycles after compaction too. From Fig. 1, it can be seen that due to wetting and drying cycles after compaction, a soil at a specific water content may exist at different suctions [5]. This emphasizes the need to measure soil suction rather than water content.

The primary objective of this paper is to summarize the initial findings of a field instrumentation project to remotely measure the real-time temporal variation of matric suction and temperature within the foundation layers of a heavy haul railway line near Ermelo in South Africa. Suction measurement techniques are briefly reviewed in order to select appropriate instrumentation for use in the field. The site

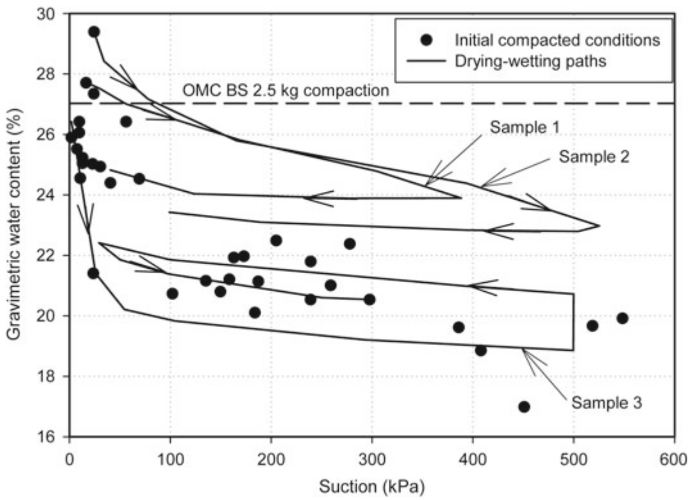


Fig. 1 Suction measurements on Kiunyu gravel (Adapted from Toll [6])

selection and positioning of the sensors are also discussed. The initial data is presented with focus on temporal variations with rainfall events.

2 In-Situ Measurement of Soil Suction for Transportation Infrastructure

The measurement of soil suction is vital for the implementation of unsaturated soil mechanics [7]. However, the literature on the in-situ measurement of soil suction within railway foundations is very limited. Furthermore, only some literature is available in this regard pertaining to pavements. This may be due in part to the difficulties associated with the field measurement of soil suction [8].

Suction measurement techniques can be divided into direct and indirect techniques. Direct techniques comprise techniques that directly measure the tensile stress in the soil–water phase. Indirect techniques rely on an intermediate relationship to proceed from a measured parameter to a soil suction value. These techniques are then further subdivided according to whether they measure total or matric suction [9]. A range of typical measurement techniques is summarized in Table 1.

Psychrometers are not ideal for field use as they are highly temperature sensitive; this temperature sensitivity increases as one approaches saturation [8]. This phenomenon is well explained by Kelvin's law.

The filter paper method is not suited for site use as the filter paper must be physically weighed upon removal from the soil, trying to mitigate any moisture loss which can result in the accumulation of significant errors merely seconds after

Table 1 Techniques for the measurement of soil suction (Adapted from Masrouri et al. [9])

Sensor	Direct/indirect	Suction component	Suction range (MPa)	Principle
Tensiometer	Direct	Matric	0–1.5	Negative pore-water pressure
Thermal conductivity	Indirect	Matric	0.01–4	Thermal conductivity of porous block
Fixed-matrix porous disk	Indirect	Matric	0.01–100	Water content of porous disk
Filter paper	Indirect	Matric/total	0.1–3	Water content of paper
Psychrometer	Indirect	Total	0.1–100	Relative humidity

removal [10]. Filter papers take more than seven days to equilibrate, which limits the practicality of observing temporal changes.

Thermal conductivity sensors showed some potential for field use according to Van der Raadt et al. [11]; however, their response times were slow and expensive signal conditioning equipment was required. Due to the circuitry of the thermal conductivity sensors, readings of suction can only be taken during site visits [12]. Thermal conductivity sensors also display some hysteresis. Therefore, a sensor installed in an initially wet condition and one installed in an initially dry condition may read different values of suction after equilibration [13]. Difficulties in the utilization of these field measurement techniques meant that seasonal changes in suction were only partially identified by Van der Raadt et al. [11]. If temporal variations of soil suction are to be monitored accurately, alternative measurement techniques have to be explored.

High-capacity tensiometers now regularly measure matric suction up to 1500 kPa [14]. Tensiometers utilize a direct technique for the measurement of matric suction and are, therefore, the instrument with the highest potential accuracy if calibrated and installed correctly. Tensiometers are not subject to the hysteresis associated with many of the indirect measurement techniques. High-capacity tensiometers have been successfully used to measure suction in-situ in a trial embankment near Newcastle, UK [15]. Despite the advantages of tensiometers, these instruments still require regular maintenance and careful consideration during the installation process and may cavitate after prolonged use.

2.1 Previous Studies

Van der Raadt et al. [11] used thermal conductivity sensors, thermocouple psychrometers and filter papers to measure soil suction near railway lines in Canada. Culverts were installed vertically adjacent to the railway at six different locations to a depth of 6 m. Holes were drilled in the sides of the culverts to access the soil at various depths within the profile. The measurements were only taken during site visits as the suction measurement techniques utilized did not lend themselves to remote and continuous logging.

A novel in-situ suction measurement technique was explored by McCartney and Khosravi [16]. They augered a hole in the pavement shoulder and backfilled the hole with silica flour within which they buried volumetric water content (VWC) sensors at different depths. An SWRC for the silica flour was measured in the laboratory. The VWC values were used to back-calculate the suction within the silica flour using the SWRC. Due to thermodynamic considerations, the soil suction in the silica flour is in equilibrium with the soil suction in the pavement layers within which it is located. No other methods were used to compare the novel SWRC back-calculation method against other existing methods [16].

The accuracy of the SWRC back-calculation method is subject to numerous factors warranting further investigation. These factors include:

- Hysteresis of the SWRC of the silica flour
- The accuracy of the VWC determination in the silica flour in the field
- Difference in dry density between the SWRC silica flour and the in-field silica flour
- Potential volume change characteristics of the silica flour.

3 Soil Suction Measurement Techniques Utilized

Three soil suction measurement techniques were utilized in this study. These techniques are summarized in the proceeding sections.

3.1 Tensiometers

Low-cost tensiometers have been developed at the University of Pretoria with a material cost of approximately US$30 each [17]. The tensiometers regularly reach cavitation pressures above 500 kPa. The calibrations done on these tensiometers show a deviation from linearity smaller than 0.1% for the calibration range (0–700 kPa). There is no apparent hysteresis in the sensors, and absolute error is less than 0.5 kPa over the full range. These factors indicate that with good contact between the tensiometers and the soil–water, the sensors will provide accurate readings of the matric suction.

3.2 Fixed-Matrix Soil–Water Suction Sensors

Commercial fixed-matrix soil–water suction sensors are fairly new to the market. The sensors make use of a porous ceramic with a fixed pore size distribution as a dielectric material. The VWC of the porous ceramic is then measured using the capacitance technique [18]. An SWRC for the porous ceramic is determined by the manufacturer and used to relate VWC to suction.

The accuracy of these sensors is still being studied, and some research into this has been conducted by Tripathy et al. [19]. A study on older versions of the sensors by Malazian et al. [20] suggests that there is significant sensor-to-sensor variability, requiring individual calibration of each sensor. Unfortunately, new models of these sensors output a value of suction directly using a pre-programmed calibration curve from the manufacturer. This does not allow for laboratory calibration by the user. The manufacturer of the sensor used in this study gives a rated accuracy of $\pm$ (10% of the reading + 2 kPa) in the range 9–100 kPa [21]. Ultimately, the accuracy of these sensors still requires more research and information from the manufacturer is limited.

3.3 Silica Flour Technique

The silica flour back-calculation technique proposed by McCartney and Khosravi [16] was also used in this study. The silica flour has a modified AASHTO maximum dry density of 1648 kg/m^3 at an optimum gravimetric moisture content of 19.2%. The θ-SWRC of the silica flour material used in the study is shown in Fig. 2. The continuous tensiometer technique [22] was used to determine the SWRC of the silica flour at a dry density of 92% modified AASHTO maximum dry density. This value was arbitrarily chosen, and the influence of dry density on the θ-SWRC requires further investigation.

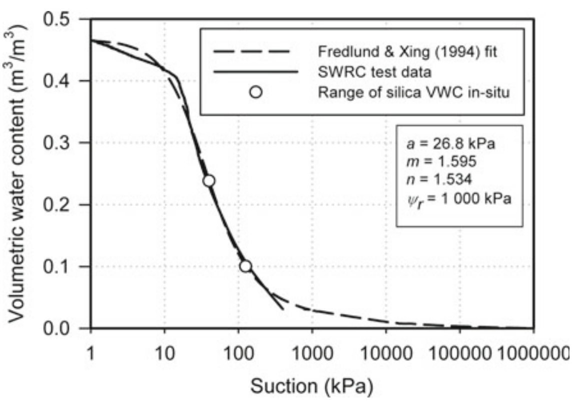


Fig. 2 SWRC of silica flour at 92% modified AASHTO maximum dry density

The Fredlund and Xing [23] equation was used to fit a mathematical relationship to the SWRC data (Fig. 2). The equation fixes the suction at a VWC of 0 m^3/m^3 to a value of 1,000,000 kPa. There are no suction data for the silica flour beyond 400 kPa, and the SWRC appears to be approaching residual conditions near this point. The fitting parameters are also indicated in Fig. 2.

The VWC of the silica flour was measured using soil moisture probes utilizing the capacitance technique. The Topp [24] equation was used to convert the measured dielectric permittivity to VWC. The Topp [24] equation is shown in Eq. (1) where θ_v is the VWC (m^3/m^3) and K_a is the dielectric permittivity (dimensionless) measured by the sensor.

$$\theta_v = \left(-5.3 \times 10^{-2}\right) + \left(2.92 \times 10^{-2}\right) K_a - \left(5.5 \times 10^{-4}\right) K_a^2 + \left(4.3 \times 10^{-6}\right) K_a^3 \tag{1}$$

The VWC of the silica flour measured in the field to date is bound by the two dots as indicated in Fig. 2. This indicates that the range of suctions in the field falls within the region of the SWRC where reasonable accuracy can be expected based on an analysis of the curve's slope.

4 Site Layout and Sensor Installation

A railway foundation on the Ermelo-Majuba Heavy Haul Coal Line was instrumented on July 26, 2019. The railway line was new and had not been opened to rail traffic yet presenting a good opportunity for the installation. The foundation layers are illustrated in Fig. 3 which also indicates the relative locations of the installed sensors.

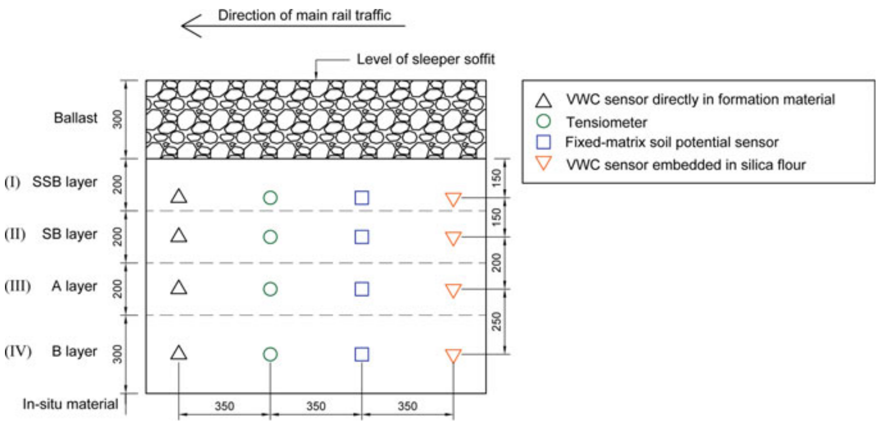


Fig. 3 Longitudinal section indicating the location of the installed sensors within the foundation layers

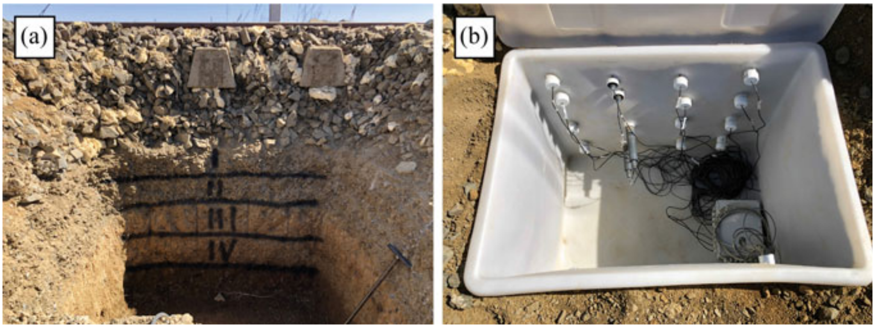


Fig. 4 **a** Excavated pit showing the constructed foundation layers. **b** Man hole to facilitate maintenance operations on the sensors if required

The foundation consists of the special subballast (SSB), subballast (SB) and placed fill (A and B) layers. These layers will henceforth be denoted by their abbreviations. The sensors used in this study were buried within every layer of the foundation. No instrumentation was buried in the subgrade beneath the B layer. All layers conform to Transnet Freight Rail's specification for earthworks [25]. Figure 4 shows photographs of the exposed layer works as well as the final installation. A weather station was also installed at the site to record air temperature, relative humidity, solar radiation, wind speed and precipitation.

A pit was excavated adjacent to the railway line as shown in Fig. 4. This pit facilitated access to the foundation layers of the railway structure. Horizontal holes were bored approximately 500 mm beyond the edge of the sleeper toward the center line of the track. PVC tubes were inserted within the bored holes to facilitate sensor maintenance. With the exception of four VWC sensors, each sensor was buried within silica flour material to improve the soil–water interface between the sensor and the railway foundation material. The four VWC sensors that were not buried in the silica flour material allowed direct measurement of the VWC of the foundation layers.

5 Results

Preliminary results are presented with a focus on the data for the month of September 2019. The sensors are assumed to have equilibrated during the month of August 2019. Precipitation was recorded for two days in September with 2.0 and 0.5 mm of rainfall occurring on 6 and 23 September, respectively. This period is regarded as a typically dry season at this location.

5.1 *Tensiometer and Fixed-Matrix Soil–Water Suction Sensor Results*

The suction data from the tensiometers is shown in Fig. 5. The suction in the SSB layer fluctuated daily with temperature and relative humidity. It is suspected that this tensiometer was not in good contact with the soil–water and requires maintenance and possible reinstallation.

Despite the fluctuations, the tensiometer in the SSB layer still responded to the rainfall events. The tensiometer in the SB layer responded to the 2 mm rainfall event but not the 0.5 mm rainfall event. The suction in the SB layer decreased from 32 to 17 kPa over a 2-week period after the 2 mm rainfall event. The A and B layers showed no response to the rainfall events and maintained a fairly constant suction value of approximately 10 kPa. Therefore, the suction response to rainfall events appears to be inversely related to depth as might be expected. Comparing the magnitude of the suctions in the layers before the first rainfall event, it can be seen that in general the suction appears to decrease with depth into the foundation.

It is insightful to compare the tensiometer suction data with the fixed-matrix soil–water suction sensor data. Daily average suction readings were calculated for the tensiometers and fixed-matrix soil–water suction sensors and are plotted against each other in Fig. 6. The data for the SSB layer has been omitted due to the tensiometer fluctuations. Points plotting on the 45° line would indicate exact correlation between the two sensors for that layer.

The suction data from the sensors in the A and B layers shows better agreement than the SB layer sensors. The A and B layers' suction data maintains a fairly constant offset of not more than 10 kPa. The data for the SB layer indicates that there is a lag between the response of the fixed-matrix soil–water suction sensor and the tensiometer but that after equilibration a fairly constant offset is also achieved. The fixed-matrix soil–water suction sensors were consistently reading larger suctions than the tensiometers.

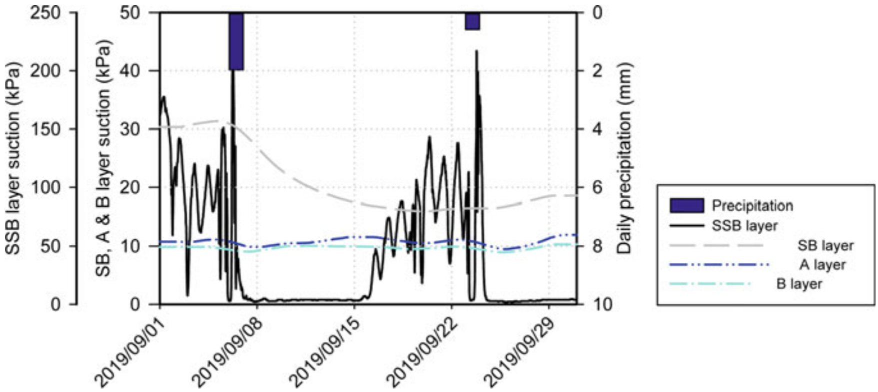
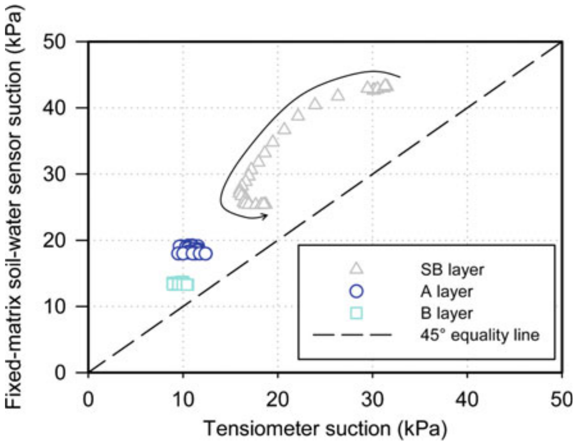


Fig. 5 Temporal variation of suction measured by the tensiometers

Fig. 6 A comparison of the suction readings between the tensiometers and the fixed-matrix soil–water suction sensors using daily average suction readings



5.2 *Back-Calculation of Suction from Silica Flour Volumetric Water Content*

The VWC of the silica flour was used to back-calculate the soil suction as described in Sect. 3.3. This data is compared to the data from the fixed-matrix soil–water suction sensors as the techniques are similar in concept. These results are shown in Fig. 7. The black-fill markers indicate data from the fixed-matrix soil–water suction sensors, and the white-fill markers indicate data from the back-calculation procedure. Data from the same layers is plotted using the same symbols.

The SSB and SB layers are the only layers which respond to the rainfall events, similar to what was observed for the tensiometer data. In general, the back-calculated

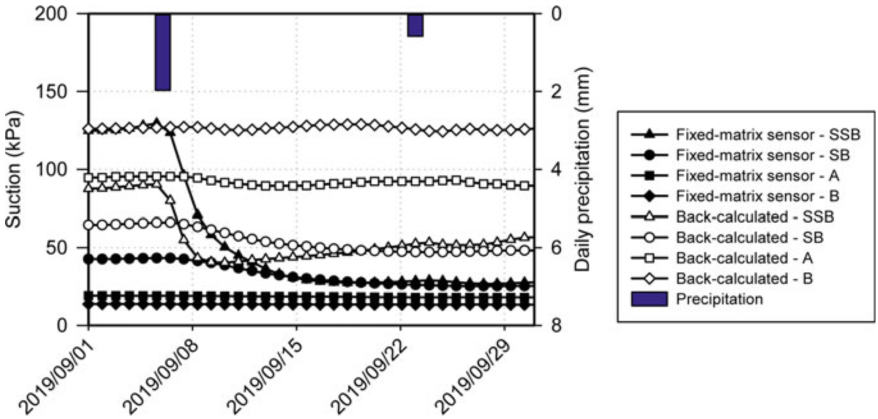


Fig. 7 Comparison of the suction readings obtained from the fixed-matrix soil–water suction sensors and the SWRC back-calculation procedure

data does not agree well with the suction data from the fixed-matrix soil–water suction sensors other than displaying similar trends for the SSB and SB layers. The difference in suction values between the two measurement techniques applied for the A and B layers is significant. Differences as large as approximately 100 kPa are evident.

There may be numerous reasons for the significant difference in suction values between the back-calculation procedure and the fixed-matrix soil–water suction sensors. The dry density between the SWRC sample in the laboratory and the silica flour in the field may be significantly different [26]. Furthermore, there may exist air gaps between the tines of the VWC sensor and the silica flour for the A and B layers, causing them to read a relatively low VWC and resulting in the high back-calculated suction values for these layers. Overall, further investigation in the laboratory under controlled conditions is required.

5.3 Soil Temperature

Figure 8 shows the temporal variation in soil temperature and air temperature recorded for September 2019. Small daily fluctuations in temperature can be seen for the SSB layer (<1 °C). The other layers appear to show no response to daily air temperature changes.

The air temperature data for the observational period shows minimum and maximum air temperatures of −5 and 31 °C, respectively. Contrastingly, the soil temperature only varied between 13 and 17 °C. This is due to the high thermal mass of the soil. A general increasing trend is observed for both the air and soil temperatures as the seasons shift toward the warmer summer months.

There is a significant response of soil temperature to rainfall events as the cold water infiltrates the surface layer of soil. The air temperature variation was also subdued during this period which may be a contributing factor. However, the soil temperature decreases significantly after both rainfall events which cannot be solely

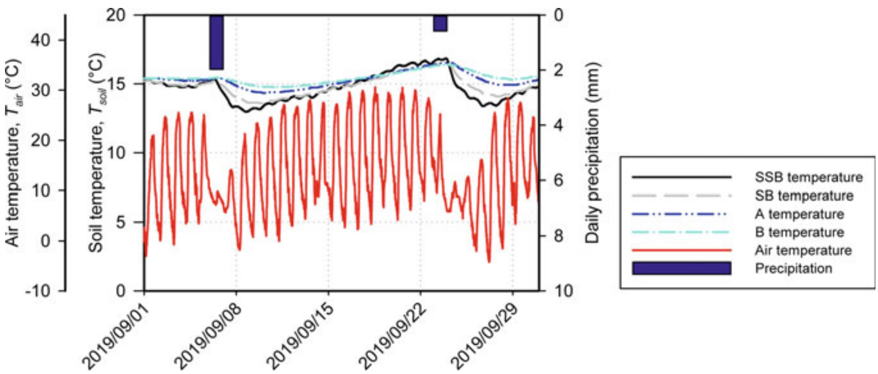


Fig. 8 Temporal variation of soil and air temperatures and the influence of rainfall

due to the subdued air temperature variation. The temperature decrease in the soil is inversely related to depth with the shallowest layer experiencing the largest decrease in temperature after both rainfall events.

6 Conclusions

A heavy haul railway foundation on the Ermelo-Majuba Coal Line in South Africa was successfully instrumented with volumetric water content (VWC) sensors, fixed-matrix soil–water suction sensors and tensiometers. A weather station was installed on the site to monitor climatic variables. The data was retrieved remotely and monitored in real time.

Three tensiometers appear to be giving reliable suction data in the subballast (SB) and placed fill (A and B) layers. The tensiometer in the special subballast (SSB) layer requires maintenance to ensure that it is well connected to the soil–water as it is fluctuating abnormally. The fixed-matrix soil–water suction sensors agree with the tensiometer suction data within 10 kPa over the observational period this far. All the suction sensors in the SSB and SB layers showed a suction decrease with an observed 2 mm rainfall event. The magnitude of the suction decrease is inversely related to the depth of the sensor.

Soil temperature appears to decrease significantly in response to rainfall events. The soil temperature in all four of the monitored layers responded to two small rainfall events of 2.0 and 0.5 mm. The magnitude of the response is inversely related to the depth of the layers with the shallowest layers showing the largest change in temperature.

A back-calculation procedure was used to calculate soil suction from the VWC of silica flour in the foundation layers. This procedure showed poor agreement between the tensiometer and fixed-matrix soil–water suction sensor data. Further research is required to identify and measure the influencing factors of this novel method in order to improve its accuracy to an acceptable level.

The field instrumentation described in this paper provides reliable real-time measurement of soil suction, temperature and weather conditions. In the long term, this would make a significant contribution toward the study of climate change and environmental conditions on the behavior of railway foundations and transportation infrastructure in general.

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