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A neutron scattering soil moisture measurement system with a linear response

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HIGHLIGHTS

- A moisture measurement system was designed and constructed.
- The system was built with an ^{241}Am/Be neutron source and two BF_3 detectors (one near and the other far from the source).
- Monte Carlo simulations and measurements showed the ratio of the near–to–far detector response was liberally proportional to the moisture up to 25% water content.

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ABSTRACT

A prototype moisture measurement system was designed and constructed, based on neutron scattering, for preforming measurements in the laboratory. The system consisted of a rectangular soil container, an ^{241}Am/Be neutron source and two parallel $^{10}BF_3$ detectors (one near the source and the other far from it). Neutrons from the source are moderated and backscattered within the soil sample before being detected by two parallel counters, whose count ratios are shown to be linearly related to the soil moisture even within short measurement times. The system's performance was demonstrated using the Monte Carlo simulations, and a series of measurements on soil samples made of clay (40 wt%) and sand (60 wt%), mixed with different percentages of water. The results showed that the detectors response ratio is linear, up to about 25% of water content.

1. Introduction

Moisture content and density are important properties of soils, to know the water content in soil is important for meteorological, hydrological and agriculture researches. Soil moisture is related to water evaporation that is linked to heat flux from land to atmosphere, also water content in soils is important in crop production, water budgeting, irrigation scheduling, particularly under the pressure of climate changing conditions (Mitra et al., 2012). The humidity in rocks is important for the exploration and development of mineral deposits in the mineral industry (Grozdanov et al., 2018). Soil water availability is important in crops production, since the determination of soil moisture in different crops and soils to regional scale is a challenging task (Uniyal et al., 2017), also the measurement of soil moisture is important in another areas like civil engineering, archeology, hydrological modeling for risk evaluations, etc.

Soil moisture is determined through direct and indirect methods. Gravimetric technique is one of the direct methods, where soil sample is oven–dried, and is widely used because it is simple, accurate and reliable (Hoogsteen et al., 2015). However, time consuming, labor intensive and costs, for continuous applications in large catchments are some of the drawbacks of direct methods. Indirect methods are simple, for continuous operations are easy to be implemented. Indirect methods include γ–ray attenuation, neutron scattering (Meigh and Skipp, 1960), remote sensing techniques as well as tensiometric, hygrometric and electromagnetic techniques (Uniyal et al., 2017), and the time–domain electric charge reflectometry, which is based on the variation of electric permittivity of the soil (Srivastava et al., 2016).

In neutron scattering techniques, the source neutrons that reach the soil are moderated and thermalized in interactions with hydrogen, before they enter the detector sensitive volume and the detector signal is further related to the amount of water in the soil. Neutron scattering

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is also used for the detection of non–metallic landmines. The plastic in the mine has a large hydrogen composition and buried in dry sand or soil the mine becomes a hydrogen anomaly that is detected by measuring the thermal neutron flux produced by the moderation and thermalization of neutrons from a source (Elsheikh, 2017). The amount of thermal neutrons moderated in the soil and are backscattered through the detector depend upon the hydrogen content in the soil and the thermal neutron signal is very sensitive to changes in the stand–off distance, which is defined as the distance between the source and the detector. Thus, in order to prevent the effect of stand–off distance on the measurement results, it was necessary to use two thermal neutron detectors separated by certain distance (Datema et al., 2001, 2002).

Neutron scattering is efficient, fast, reproducible, economic, non–-destructive, reliable with a relatively high accuracy and optimal for use in rocky soil (Su et al., 2014; Bogena et al., 2015). The use of neutron scattering for moisture detection, since its introduction more than 50 years ago (Meigh and Skipp, 1960), found wide use in agriculture, forestry and infrastructures such as road and dam constructions, coal and iron mines, etc. (Zhu et al., 2013).

Nevertheless soil moisture measurement using neutron scattering is a mature technique, it is important to review the security and safety concerns of the neutron source, to analyze the effect of using different neutron sources, like isotopic or neutron generators, and the effect of using two thermal neutron detectors instead of using only one, as was suggested in the detection of buried non–metallic mines (Datema et al., 2001, 2002).

The aim of this work was to design a soil moisture measurement device (SMM) with two thermal neutron detectors and an ^{241}Am/Be radioisotopic neutron source, here the effect of the detectors positions were analyzed. Also, in the design, the detector responses to monoenergetic neutrons of the SMM were estimated with the purpose of evaluate the best mean neutron energy.

The ^{241}Am/Be neutron source has a half–life ($t_{1/2}$) of 432.6 years, the mean neutron energy ($\bar{E_n}$) is 4.16 MeV these values are larger than those for ^{252}Cf ($t_{1/2}$ = 2.6 y, $\bar{E_n}$ = 2.13 MeV) (Cester et al., 2016). Neutron spectrum and dosimetric features are well known (Vega, Carrillo and Martinez, Ovalle, 2016); among (α, n) sources ^{241}Am/Be has the highest neutron emission probability (~67.6 n/s for every megabecquerel of alpha emitter) (Knoll, 2010). It is also inexpensive and readily available (Mitra et al., 2012).

This work was carried out in two stages of using the Monte Carlo code MCNPX2.6 (Hendricks et al., 2008) incorporating ENDF/B–VII cross section library (Chadwick et al., 2011), where two different cases were calculated (with and without density gradient considerations, which is due to earth's gravitation), as well as building and testing the SMM, and finally comparing the results with the Monte Carlo simulations to emphasize the linearity of the proposed SMM device.

2. Monte Carlo simulations

The SMM setup used in this work aimed at develop a device for use in the laboratory. Since the preparation of large soil sample of uniform moisture and with different water contents is difficult and time–-consuming, it is desirable to perform measurements with as small soil sample as possible. Therefore, it was first decided to determine the optimum soil sample for the SMM using the MCNPX code. For this purpose, the simulations were made for a soil sample (500 × 500 × 350 (depth) mm^3) with a gradual increase in height (from 0 to 300 mm), using the simulation setup of Fig. 1. The composition of standard soil (U.S. average Earth) used in the Monte Carlo calculation is shown in Table 1 (McConn et al., 2011). The simulated LND2025 BF_3 counter detector (LND2025) had the gas pressure and the ^{10}B enrichment of 550 Torr and 96%, respectively. BF_3 was selected, over other detectors, such as those incorporating ^{3}He and ^{6}Li, because it is relatively inexpensive, easy–to–handle and also it produces much greater electron–ion pair per absorbed neutron (Crawford, 1993).

As seen in Fig. 2, in both near and far detectors (the detectors near the source and far from it), the detector reaction rates are altered very slightly as the soil sample height rises up around 300 mm. Hence, in this study, the rest of both simulations and measurements were replaced a soil sample of maximum 300 mm height.

The MCNPX Monte Carlo was also used to study the effect of neutron energy on the detector response, using a set of monoenergetic point sources: energies were 10^{-6}, 10^{-5}, 10^{-4}, 10^{-3}, 10^{-2}, 10^{-1}, 1 and 10 MeV. A 500 × 500 × 350 (depth) mm^3 rectangular soil container (with different water contents, from 0% to 20%), sufficiently large to represent an extended soil environment.

A simulated LND2025 BF_3 counter detector (LND2025) was positioned at the top of the soil sample, and a point isotropic mono–-energetic neutron source was at the same elevation from the soil, 100 mm away from the detector. The MCNPX F4 tally, with the (n,α) reaction, was used to estimate the neutron fluence of the detector. The number of histories was 10^7, which allowed uncertainty less than 3%. As it can be seen in Fig. 3, the count rates registered by both near and far detectors are considerably increased when the source neutron energies decrease to thermal region, due to large (n_{th},α) cross section of ^{10}B.

Having denoted the difference between the near and far detectors count rates as ΔCR, the results of Fig. 3 can be summarized as follows: Because the cross–section of neutron elastic scattering off hydrogen nuclei decreases with the increase in neutron energy, the water content does not considerably improve the neutron thermalization in this energy range, and hence, the counts registered by near and far detectors does not differ much. This will results in small ΔCR for the case of low water content and high neutron energy. Alternatively, when the soil sample is exposed to low–energy neutrons, although the count rates of both near and far detectors for high water content is very high but the neutron capture reactions also increase which results is an overall large ΔCR.

Therefore, the conclusion may be drawn that if one uses an isotopic neutron source, where both low and high energy neutrons are present, ΔCR may result in non–small values for a range of soil moistures and it is apparently enhanced with increasing water content, which is the main idea behind the use of count ratio (i.e., the count rates of near to far detectors) in the present study.

The setup of Fig. 1 was simulated, including the 500 × 500 × 350 mm^3 rectangular soil box, a cylindrical ^{241}Am/Be neutron source (50 mm dimeter by 100 mm length cylinder, left) and two parallel BF_3 counters (225 mm diameter by 155 mm length cylinder, right). Second BF_3 was located near and parallel to the first, and the source, near and far detectors are arranged at +180 mm, +320 mm and +460 mm to the left edge of the soil container (which is set as origin), respectively. Both neutron sources and detectors are placed in cylindrical holders. Since the neutron counter is a BF_3 enriched in ^{10}B with a high neutron absorption cross−section at the thermal energy while the neutron source is an ^{241}Am/Be with almost zero thermal neutron emission probability, one would expect that the source neutrons, directly incident on the detector surface, not to be detectable, however, in practice both detectors register counts because other materials in the soil can moderate high energy neutrons from neutron source.

Fig. 4 shows the near–detector response divided by that of the far–detector called as near–to–far response against the water content at a 300 mm height.

The sensitivity of an SMM system is enhanced and the system calibration is facilitated when its response exhibits a linear behaviour with a reasonable slope. The linearity improvement can be investigated by fitting a polynomial to the data points and then comparing the relative errors of fitting parameters. To this purpose, a fifth–order polynomial was fitted to the data of Fig. 4 (300 mm soil height) as well as those of Fig. 2. Both the fitting parameters and their uncertainties are listed in Table 2. The relative error of a fitting parameter determines whether or

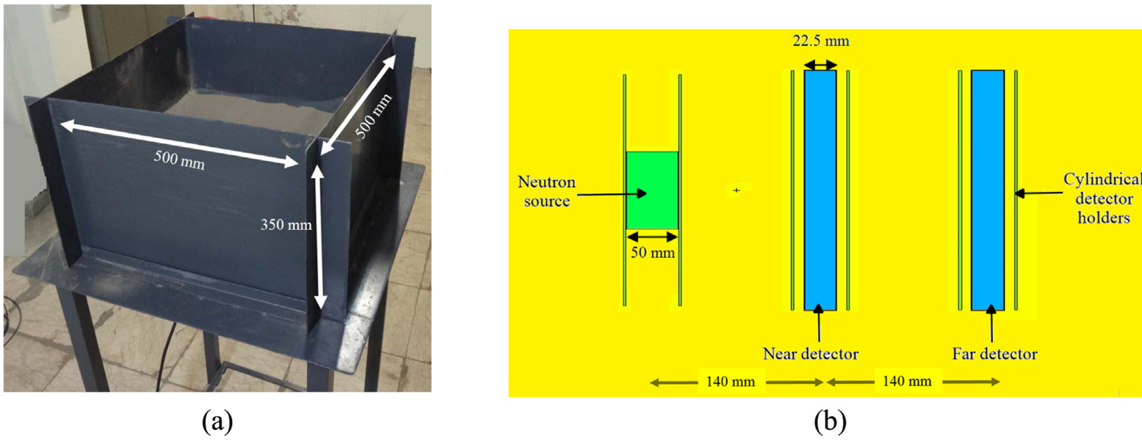

Fig. 1. Configuration of SMM system: (a) Side view and (b) Cylindrical neutron source and two cylindrical BF_3 neutron counters located inside cylindrical iron holders.

Table 1
Elemental concentration in standard soil (U.S. average Earth) (McConn et al., 2011).

Element	Weight fraction
O	0.513713
Na	0.006140
Mg	0.001330
Al	0.068563
Si	0.271183
K	0.014327
Ca	0.051167
Ti	0.004605
Mn	0.000716
Fe	0.056283

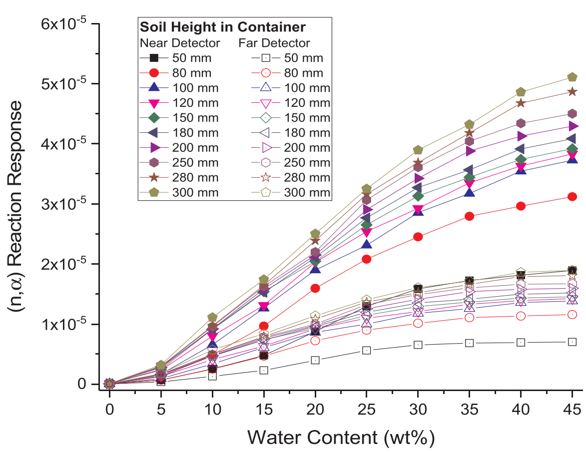

Fig. 2. Detector response versus water content for a soil sample of different height (from 0 to 300 mm) with an ^{241}Am/Be neutron source for: Near and Far detectors. The detector–to–detector distance remains fixed at 140 mm.

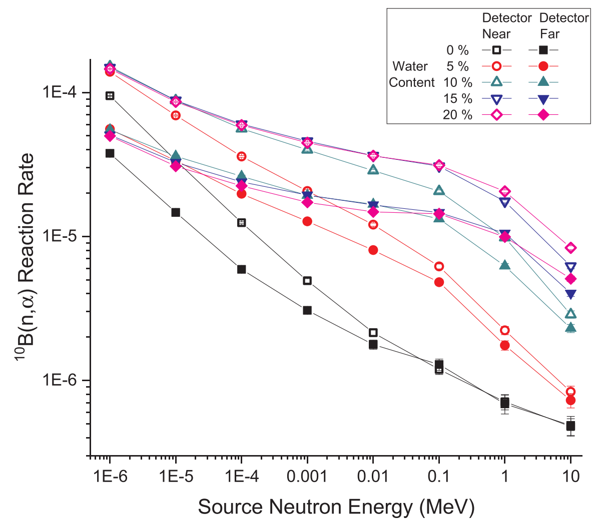

Fig. 3. Total tally response against neutron source energy for both near and far detectors when the soil sample of different water contents (from 0% to 20%) is exposed to monoenergetic neutrons.

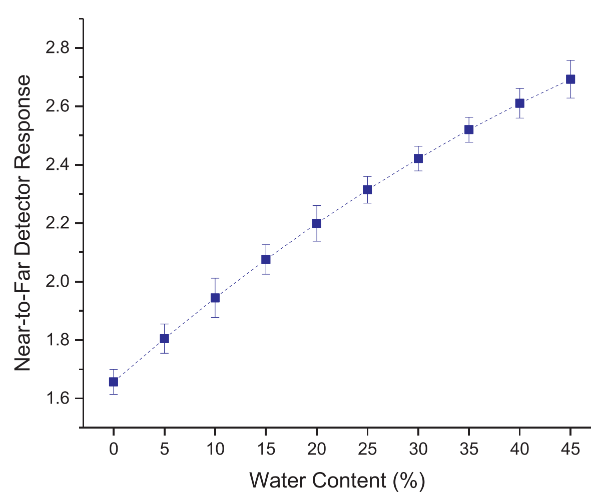

Fig. 4. Variation of near–to–far detector response with water content of a soil sample at a 300 mm height irradiated with ^{241}Am/Be neutron source.

not the corresponding term is worth to be included. As it can be seen, the relative errors of zeroth and first order terms (i.e., $\Delta P_0/P_0$ and $\Delta P_1/P_1$) of near–to–far data are very small compared to those of its higher–order terms and also very much small compared to those of both far and near data. Therefore, one may conclude that a straight line is more appropriately fit the near–to–far data.

3. Experimental measurements

The system shown in Fig. 1 was constructed for testing in the laboratory. The holders for the source and two detectors were made of

Table 2
Relative errors of fitting parameters for a fifth–order polynomial fitted to three different set of data.

		Fitting model: $y(x) = P_0 + P_1x + P_2x^2 + P_3x^3 + P_4x^4 + P_5x^5$					
		Relative error of fitting parameters					
		$\Delta P_0/P_0$	$\Delta P_1/P_1$	$\Delta P_2/P_2$	$\Delta P_3/P_3$	$\Delta P_4/P_4$	$\Delta P_5/P_5$
Detector count rate	Far	43.15881	1.00721	0.53502	0.64064	0.80035	0.93807
	Near	56.88734	1.49943	0.53852	0.77473	1.04883	1.25003
	Near to far	1.54646E–6	4.6666E–5	0.00137	1.65709	1.50849	1.38633

Table 3
Constituent elements of soil sample analyzed with XRF.

Element	Relative weight (%)
Al	7.5350
Ca	30.7060
Cl	0.0282
Co	0.0440
Fe	6.8120
K	3.0350
Mg	2.0290
Mn	0.0194
Na	0.0724
P	0.0155
Rb	0.0150
S	0.2470
Si	33.3530
Sr	0.0228
Ti	0.0731
Zn	0.0250

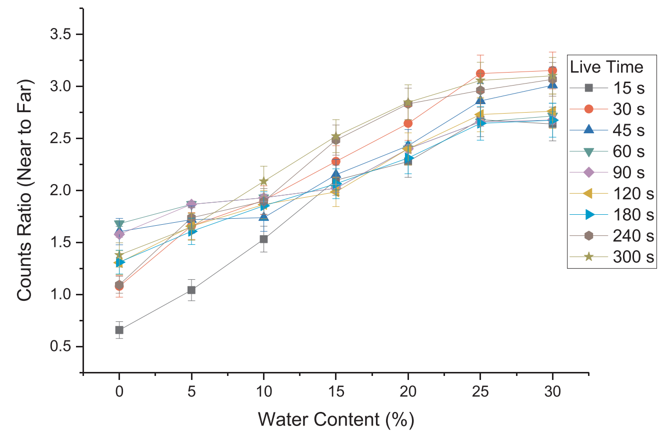

Fig. 6. Measured count rates registered with two BF_3 counters beneath the SMM system. The source was a 3.7×10^9 Bq ^{241}Am/Be.

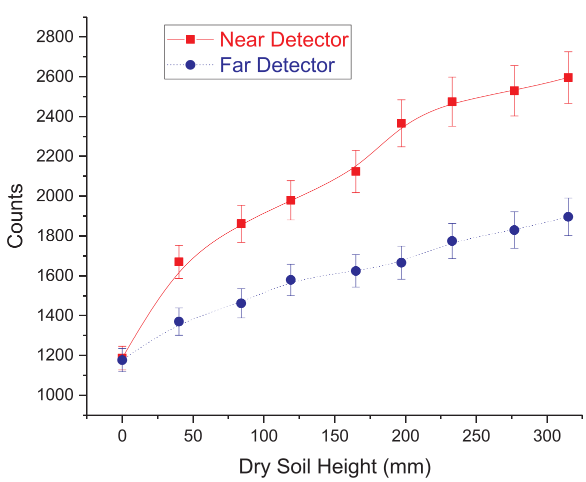

Fig. 5. Experimental data for a dry soil sample exposed to an ^{241}Am/Be neutron source for near and far detectors for 60 s live time.

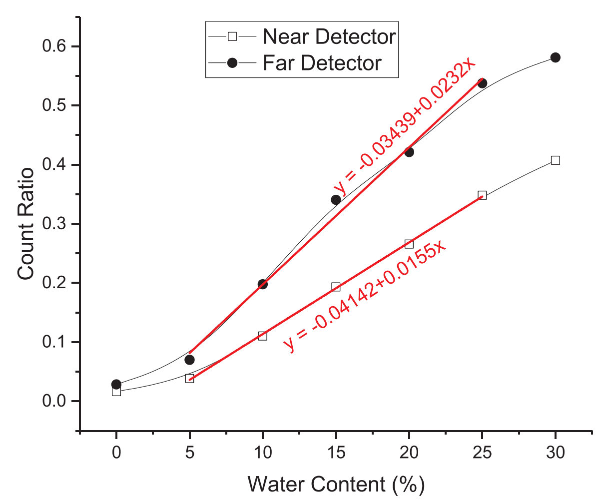

Fig. 7. The count ratio as a function of water content.

steel to reduce the manufacturing and welding costs. The nuclear electronics consisted of FAST ComTec NHQ203M HV power supply, ORTEC 142 pre–amplifier, ORTEC 672 spectroscopy amplifier, CANBERRA 8076 ADC and an MCA card. The soil constituent elements were determined using X–ray fluorescence (XRF) analysis, and listed in Table 3. The soil was well – dried before adding water and the water was uniformly mixed with the soil sample. Different weight percentages of sand and clay were mixed in small portions. After some trials, in order to prevent the formation of soil lumps, a mixture of 60 wt% sand and 40 wt% clay were founded to be suited with acceptable performance.

All measurement were carried out in the middle of a relatively large laboratory with dimensions 8 m × 15 m × 6 m height and also the soil sample was located at 1.2 m above the floor level, in order to suppress the contributions of backscattered neutrons to the detector counts. However, some discrepancies between measurements and simulations may be attributed to the unmodeled surrounding materials.

The detector counts were recorded for various dry soil height, (1) to evaluate the dry soil contribution to detector counts and also (2) to find the optimum soil height for SMM test which was previously determined with the Monte Carlo simulations. The near and far detector counts for dry soil heights of 0, 40, 84, 119, 165, 197, 233, 277, and 315 mm, which approximately correspond to 0, 15, 30, 45, 60, 75, 90, 105 and 120 kg of dry soil are shown in Fig. 5.

A completely dried 83.72 kg soil sample was also prepared for SMM. The height of the dry soil sample was 197 mm in the container. Then, an amount of water equivalent to 5 wt% of dry soil sample was added at every stage, up to 30 wt%. The counts of both near– and far–detectors when the proposed system is exposed to ^{241}Am/Be neutron source were recorded for different live time periods (ranging from 15 s to 300 s, with

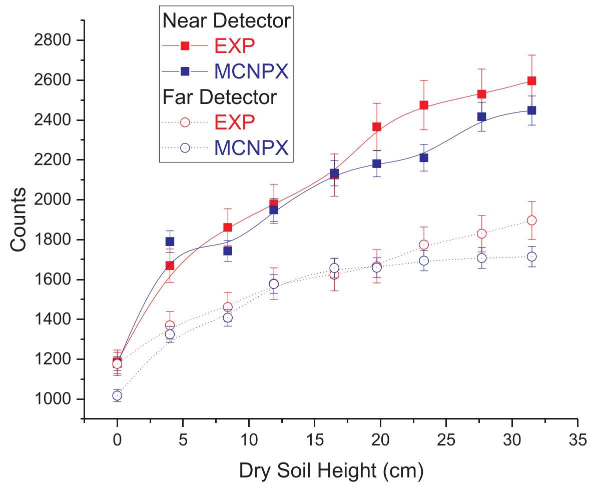

Fig. 8. Comparison between MCNPX simulation and measurement results for an SMM on a soil sample mixed with different water contents (with special density gradient discussed in the text) when exposed to an ^{241}Am/Be source.

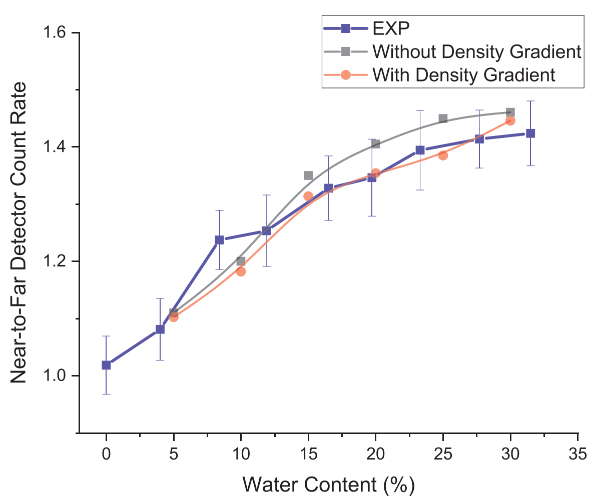

Fig. 9. The MCNPX results of the variation of near–to–far counts ratio for the proposed SMM system, with and without density gradient.

different intervals (15 s, 30 s and 60 s) to cover the whole range of 15–300 s); their ratios are shown in Fig. 6. Although the count rates of both near and far detectors increase with water contents as expected, neither of them exhibited a well linear behaviour in the whole water content range. However, the variation of count ratios versus the water content, even in short live times, shows an acceptable linearity.

Normally calibration curve has to be obtained prior to every SMM to ensure that the SMM system remains stable since both neutron source activities and detector efficiencies may change for a very long course of measurements. The calibration procedure aims to establish a quantitative association between the neutron count rate for a soil sample of a certain moisture content (i.e., N/t) and the neutron count rate for a standard substance (i.e., N_s/t_s). Here, the standard substance is high–-density (0.94 g/cm^3) polyethylene (C_2H_4). If the calibration curve is linear, one has to find only a few points for the calibration, which is the main advantage.

Fig. 7 shows the detector count rate in soil sample divided by the count rate for the standard sample, called the count ratio. The setup consists of a 233 mm high soil sample, a 3.7 × 10^9 Bq ^{241}Am/Be source. The linear region where the SMM exhibits its best performance is identified in the Fig. 7.

In order to have a more realistic MCNPX model of the proposed SMM, a density gradient was provided. Since it is difficult to model a soil sample with gradual increase in its density, the soil height was divided into five different parts of different densities so that the density increased by 10% in every layer from top to bottom. Then different weight percentages of water have been added to the dry sample. Both measurements and MCNPX simulation results are shown in Fig. 8. The comparison confirms that the difference between the measurements and simulations data are less than 5%, which represents an acceptable agreement, despite the approximations made. As seen in Fig. 9, although a precise linear behaviour all over the soil moisture range is not observed, the sensitivity of the proposed system to the water content was considerably improved.

4. Conclusions

A system for soil moisture measurement (SMM) in the laboratory is introduced. It consisted a rectangular soil container, an ^{241}Am/Be neutron source and a couple of parallel BF_3 counters, one near and far from the neutron source. The near–to–far detector count ratio, even in a very short measurement live times, was shown to provide a linear response, facilitating the use and calibration of the system. Monte Carlo simulations undertaken with MCNPX2.6 code confirmed that the measurements and simulation results are in promising agreement especially when a density gradient is considered for modeling the soil sample.

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