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Evaluating The Effectiveness of Radon Measurement Techniques in Soil Gas: Impact of Hole Depth and Measurement Time

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ABSTRACT

Radon measurement methodologies are critical for accurate risk assessment and resource optimization, yet challenges persist in determining the optimal sampling depth and measurement duration. These factors significantly influence radon concentration readings, and their impact still needs to be explored in systematic evaluations, particularly in balancing efficiency and accuracy. This study evaluates the effectiveness of radon measurement methodologies by experimenting with how sampling hole depth and measurement duration affect radon concentration in soil gas. Radon experiments were conducted at depths of 0.5 m, 1.0 m, and 1.2 m over a 39-day period in soft tuff rock formations at Institut Teknologi Sumatera. Measurements were taken on Days 0, 6, 12, 18, 27, and 39 using the RAD7 Radon Detector, with multiple cycles to ensure stability. The results indicate that radon concentrations varied significantly with both depth and time, with the highest concentrations observed at 1.2 m on Day 18 (1,089 Bq/m³). A noticeable "lag effect" was observed following rainfall events, where radon levels initially decreased due to soil saturation but spiked as the soil dried. The depth of 0.5 m provided the most consistent measurements, with the lowest coefficient of variation (CV = 31%), making it the most reliable and practical depth for routine radon assessments. Overall, this study highlights the importance of considering environmental conditions, such as rainfall and soil moisture, when interpreting radon data and provides insights into optimizing radon measurement practices for accuracy and efficiency.

Keywords: radon, soil-gas, variability, rainfall, hole depth, measurement time.

INTRODUCTION

Radon (^{222}Rn) is a naturally occurring radioactive gas resulting from the decay of uranium in soils and rocks. Being colorless, odorless, and tasteless, radon poses a significant health risk as it can accumulate in enclosed spaces without detection [1]. Prolonged exposure to elevated radon levels is the second leading cause of lung cancer after smoking, accounting for a substantial number of lung cancer cases worldwide [2]. Accurate measurement of radon concentrations, particularly in soil gas, is crucial for assessing potential exposure risks and implementing effective mitigation strategies.

Radon canalso serve as a valuable tracer in geology and geothermal exploration. Due to its mobility and ability to migrate through soil and rock, radon anomalies in soil gas can indicate subsurface geological features such as faults, fractures, and zones of increased permeability [3]. In geothermal fields, elevated radon concentrations often correlate with geothermal reservoirs because radon is transported to the surface alongside geothermal fluids through convection and diffusion processes [4]. Monitoring radon emissions assists in identifying areas of geothermal activity, which is essential for locating potential sites for geothermal energy extraction [5]. Additionally, radon measurements contribute to understanding volcanic activity and tectonic movements, enhancing the exploration and assessment of geothermal resources [6], [7].

The methodology employed in radon measurement significantly influences the accuracy and reliability of the results. Two critical factors in soil gas radon measurement are the depth of the sampling hole and the duration of the measurement period [8]. Deeper sampling holes may intercept higher radon concentrations due to increased uranium content and reduced dilution effects near the surface [9]. However, drilling deeper holes is more labor-intensive, time-consuming, and costly. Similarly, the duration of radon measurements affects the representativeness of the data. Short-term measurements can capture transient fluctuations but may miss longer-term trends, whereas long-term measurements provide comprehensive data but require extended resource allocation [3].

Previous studies have explored the effects of sampling depth and measurement duration on radon concentration readings. For instance, Hassan et al. [10] investigated soil radon concentrations at various depths and found that radon levels generally increase with depth but also depend on soil properties and environmental conditions. Additionally, Miles [11] studies highlighted the temporal variability of radon concentrations, emphasizing the need for appropriate measurement durations to obtain representative data.

This experiment aims to determine the effectiveness of radon measurement methodologies by analyzing how the depth of the sampling hole and the duration of the measurement period influence radon concentration readings. Specifically, we aim to assess whether longer measurement times and deeper holes are less effective than shorter times and shallower depths. By conducting systematic measurements of radon concentrations at depths of 0.5 m, 1.0 m, and 1.2 m over a 39-day period, we seek to optimize radon measurement practices for both efficiency and accuracy.

Our analysis compares the effectiveness of different measurement strategies to determine the most practical approach for routine radon assessments. The findings of this study are intended to inform best practices in radon measurement methodologies, potentially leading to improved risk assessments and more efficient resources allocation in radon mitigation efforts.

THEORY

Radon is a naturally occurring radioactive noble gas resulting from the decay of uranium-238 (^{238}U), which is found ubiquitously in varying concentrations in soils and rocks [1]. As part of the uranium decay series, radon is produced directly from the alpha decay of radium-226 (^{226}Ra). Due to its inert nature and gaseous state, radon can migrate freely through the pore spaces in soil and rock, allowing it to move away from its source material [9]. This migration is influenced by factors such as soil porosity, moisture content, grain size, and the presence of fractures or

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faults in geological formations [1], [4], [10]. Environmental conditions like temperature gradients and pressure differences between the soil and the atmosphere also play significant roles in facilitating radon transport from the ground into the air [10], [12].

METHODOLOGY

The experiment was conducted at the Institut Teknologi Sumatera, Lampung, characterized by soft tuff rock formations. Tuff is a type of volcanic rock composed of consolidated volcanic ash, known for its porosity and potential to influence radon emanation due to its uranium content [1]. The soil in the study area is a weathering product of tuff, characterized by a loose texture and a white-greyish color, and primarily consists of pyroclastic materials with some pumice fragments [13], [14]. The composition is uniform across all sampled depths, and no groundwater was encountered down to a depth of 1.2 m. In our research, the effect of soil properties can be neglected, as the soil/rock composition is homogenous, and the distance between sampling holes is nearby.

The impact of sampling depth on radon concentration measurements was assessed using three sampling holes with one-meter separation that were drilled to depths of 0.5 meters, 1.0 meters, and 1.2 meters, respectively (Figure 1). These depths were selected to evaluate the effectiveness of shallower versus deeper sampling. The holes were drilled using a manual auger, ensuring minimal disturbance to the surrounding soil structure. Each hole was lined with a PVC pipe to prevent collapse and to maintain the integrity of the sampling depth. The bottom of the PVC pipe was open, and screening was placed approximately 30 cm from the bottom on the wall side of the PVC to allow radon gas to enter the pipe from the surrounding soil. The top of each PVC casing was sealed with a cap and duct tape to prevent atmospheric air from diluting the soil gas samples.

(a) **(b)** **(c)**

Figure 1. Radon measurement site at Institut Teknologi Sumatera for depths 0.5 m (a), 1 m (b), and 1.2 m (c)

Radon measurements were conducted over a 39-day period, with sampling occurring on Days 0 (initial measurement), 6, 12, 18, 27, and 39. This schedule allowed for the observation of temporal variations in radon concentrations and assessing the effectiveness of different measurement durations. The RAD7 Radon Detector, manufactured by Durridge Company Inc., was used to measure radon concentrations. The RAD7 is a professional-grade, real-time monitor that utilizes a solid-state alpha detector to measure radon gas with high sensitivity and accuracy. It is widely used in radon research and is suitable for indoor air and soil gas measurements.

Prior to each measurement, the RAD7 was set up according to the manufacturer's guidelines for soil gas measurements. The instrument was configured to operate in "Sniff" mode for rapid response and real-time readings. A soil gas probe connected to the RAD7 via airtight tubing was inserted into each sampling hole, ensuring a tight seal to prevent air leaks (Figure 2). The system was purged for several minutes to remove residual air and draw soil gas into the detector. Measurements were taken for ten cycles per hole in each day, with 5 minutes of measurement in each cycle to achieve statistically reliable readings. The RAD7 recorded radon concentrations in becquerels per cubic meter (Bq/m^3) at regular intervals.

Figure 2. RAD7 measurement setting for measuring radon concentrations

Data analysis involved compiling radon concentration data from each depth and measurement day into spreadsheets for organization and analysis. Descriptive statistics such as mean, median, standard deviation, and coefficient of variation were calculated for each depth to assess the variability and central tendency of the radon concentrations. Temporal trends were analyzed to assess changes in radon concentrations over the 39-day period. Comparisons were made between the different depths to evaluate the influence of sampling depth on measurement effectiveness.

Environmental considerations were acknowledged during the experiment. The soil at the sampling site, characterized by soft tuff rock, was expected to influence radon emanation rates due to its uranium content and porosity. Although soil temperature and moisture content were assumed to be consistent, they were not explicitly measured. Measurements were scheduled to avoid adverse weather conditions, such as rain, which could affect soil gas permeability and radon concentrations. Ambient atmospheric pressure and temperature were noted but were not rigorously controlled, recognizing that these factors can influence radon levels.

The study faced certain limitations. Environmental parameters such as soil moisture, temperature, and atmospheric pressure were not continuously monitored, which could influence radon emanation and migration but were beyond the scope of this study. Additionally, the experiment was conducted at a single site, which may limit the generalizability of the findings to other geological settings. Measurements were taken at discrete intervals, potentially missing short-term fluctuations in radon concentrations.

RESULTS

The result of radon concentration measurements on Days 0, 6, 12, 18, 27, and 39 were represented in Table 1. Each measurement session includes multiple cycles to account for instrument stabilization, with the interpreted value calculated as the average of the stable readings after the initial transient cycles. From Figure 3, it can be seen that generally stable readings were acquired after the 2nd or 3rd measurement.

At a depth of 0.5 m, the interpreted radon concentrations ranged from 433 Bq/m^3 on Day 6 to 991 Bq/m^3 on Day 39, with a peak concentration of 931 Bq/m^3 observed on Day 18. At a depth of 1.0 m, the interpreted values show a range from 321 Bq/m^3 on Day 6 to 862 Bq/m^3 on Day 39, with the highest concentration recorded on Day 18 at 857 Bq/m^3.

At a depth of 1.2 m, radon concentrations showed higher values compared to shallower depths, with the interpreted values ranging from 598 Bq/m^3 on Day 6 to 1,089 Bq/m^3 on Day 18, which represents the highest radon concentration recorded across all depths and days. By Day 39, the radon concentration at 1.5 m had decreased to 649 Bq/m^3.

Table 1. Result of radon concentrations measurement for different depth and several measurements time; Each site measured at 10 cycles except on day 0 for 1 m depth due to rain (nm: not measured).

Depth (m)	Day	^{222}Rn (Bq/m^3) Cycle 1	2	3	4	5	6	7	8	9	10	Interpreted value
0.5	0	155	264	658	867	942	975	989	1010	955	984	976
	6	169	361	394	416	439	447	444	418	425	439	433
	12	148	387	497	533	563	577	564	569	547	598	564
	18	247	752	925	955	944	934	933	878	965	908	931
	27	317	616	663	686	639	679	668	639	700	710	673
	39	385	889	989	998	999	1020	986	988	986	961	991
1	0	183	247	411	436	400	422	432	416	398	nm	416
	6	228	314	308	334	327	320	315	336	306	323	321
	12	225	395	438	520	461	487	461	471	463	461	470
	18	307	680	824	823	833	844	846	894	862	857	848
	27	250	570	729	812	749	756	743	727	727	719	745
	39	345	720	908	937	881	890	843	844	786	807	862
1.5	0	175	203	586	861	988	984	993	1050	979	1089	1014
	6	153	387	491	485	599	561	590	622	624	590	598
	12	210	393	474	477	465	461	510	499	454	496	480
	18	379	843	1000	1070	1060	1080	1090	1100	1100	1120	1089
	27	305	649	836	901	908	933	927	1019	961	990	948
	39	284	615	700	659	622	664	645	636	624	696	649

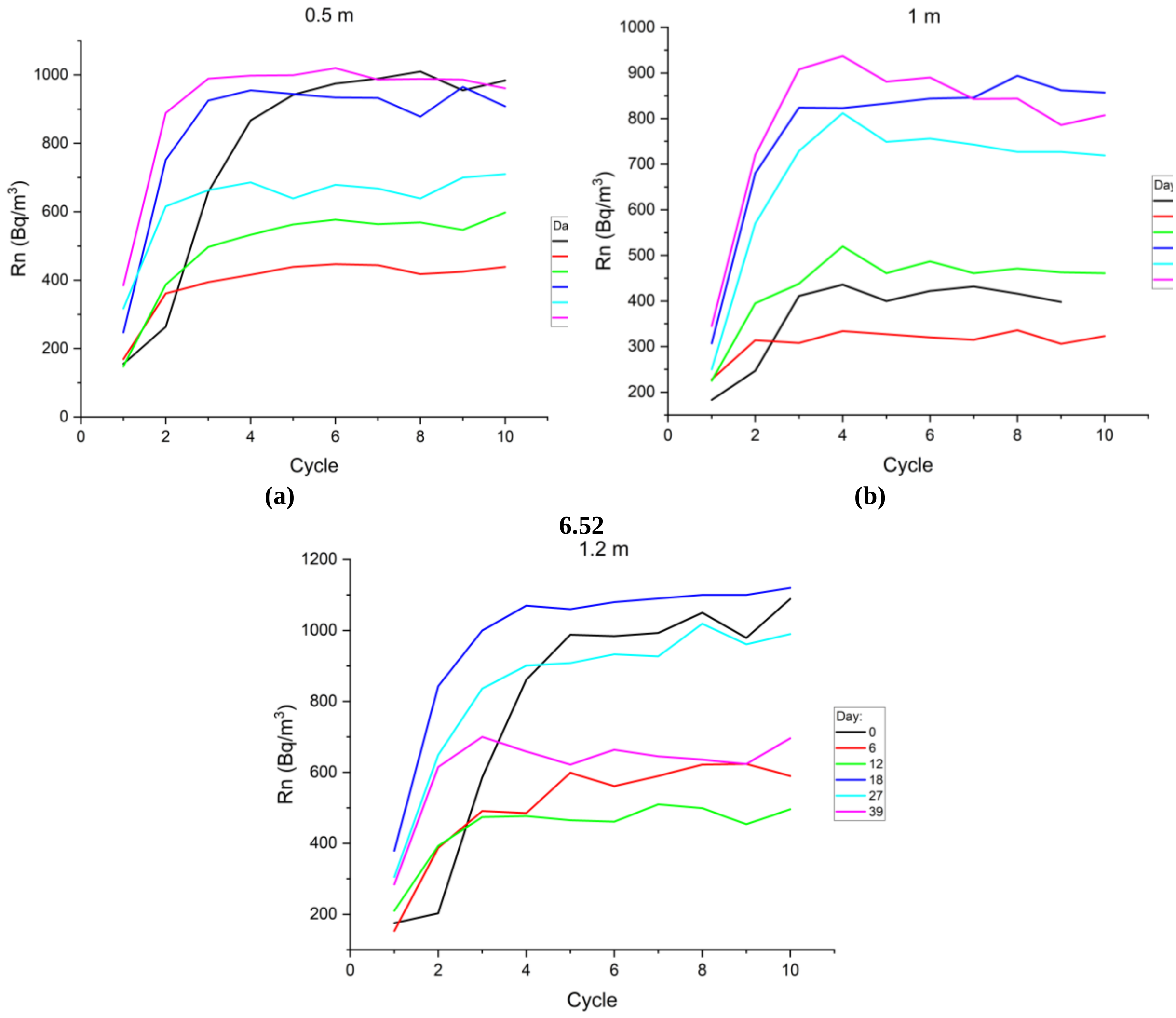

Figure 3. Graph of radon measurements comparing to the cycles at a depth of 0.5 m (a), 1 m (b), and 1.2 m (c); Generally, steady measurements were achieved after 2nd or 3rd cycles

The interpreted radon data and statistical measures such as mean, standard deviation (STDEV), and coefficient of variation (CV) were presented in Table 2. The highest radon concentrations are observed on Day 18, with values of 931 Bq/m^3 at 0.5 m, 848 Bq/m^3 at 1.0 m, and 1,089 Bq/m^3 at 1.2 m, resulting in an overall mean of 956 Bq/m^3 and a low CV of 13%, indicating relatively low variability between depths. Day 6 shows the lowest radon levels at 0.5 m (433 Bq/m^3) and 1.0 m (321 Bq/m^3), while the value at 1.2 m is higher at 598 Bq/m^3. The mean on this day is 450 Bq/m^3 with moderate variability (CV = 31%).

On Day 12, radon concentrations are more uniform across depths, with a mean of 505 Bq/m^3 and the lowest CV of 10%, indicating little variation between the depths. Day 39 exhibits relatively high radon concentrations at 0.5 m (991 Bq/m^3) and 1.0 m (862 Bq/m^3) but a lower value at 1.2 m (649 Bq/m^3), with an overall mean of 834 Bq/m^3 and moderate variability (CV = 21%).

Table 2. Radon concentration measurements (in Bq/m^3) at three depths (0.5 m, 1.0 m, and 1.2 m) over five observation days, with corresponding mean, standard deviation (STDEV), and coefficient of variation (CV)

Day	**Depth (m)**					
	0.5	**1**	**1.2**	Mean	STDEV	CV
0	976	416	1014	802	334	42%
6	433	321	598	450	139	31%
12	564	470	480	505	52	10%
18	931	848	1089	956	122	13%
27	673	745	948	789	143	18%
39	991	862	649	834	172	21%
Mean	761	610	796			
STDEV	238	236	252			
CV	31%	39%	32%			

Overall, the mean radon concentration across all days is highest at 1.2 m (796 Bq/m^3), followed by 0.5 m (761 Bq/m^3), and lowest at 1.0 m (610 Bq/m^3). The highest variability in radon concentration is observed at 1.0 m (CV = 39%), indicating more fluctuations over time at this depth. The data reveals that Day 18 and the 1.2 m depth show the highest overall radon concentrations, while Day 12 has the most consistent values across depths.

DISCUSSIONS

On average, radon concentrations decrease at a depth of 1.0 m and rise again at 1.2 m, with similar values recorded at 0.5 m and 1.2 m (761 Bq/m^3 and 796 Bq/m^3, respectively) as illustrated in Figure 4. The depth of 0.5 m provides the most reliable measurements, as indicated by the lowest CV (31%), although this is only slightly lower than the CV at 1.2 m (CV = 32%). Therefore, measuring radon at a depth of 0.5 m is the most effective approach, balancing both accurate radon concentrations and ease of labor.

The relationship between radon concentrations at three depths over time and superimposed by rainfall rate (data from UPT MKG ITERA) illustrated in Figure 5. Initially, radon concentrations were relatively high across all depths on Day 0, with the highest concentrations observed at 0.5 m and 1.2 m. By Day 6, radon levels drop significantly across all depths, coinciding with the onset of rainfall, particularly at 1.0 m and 0.5 m. The decrease in radon suggests that the rainfall is likely to suppress radon exhalation by saturating the soil.

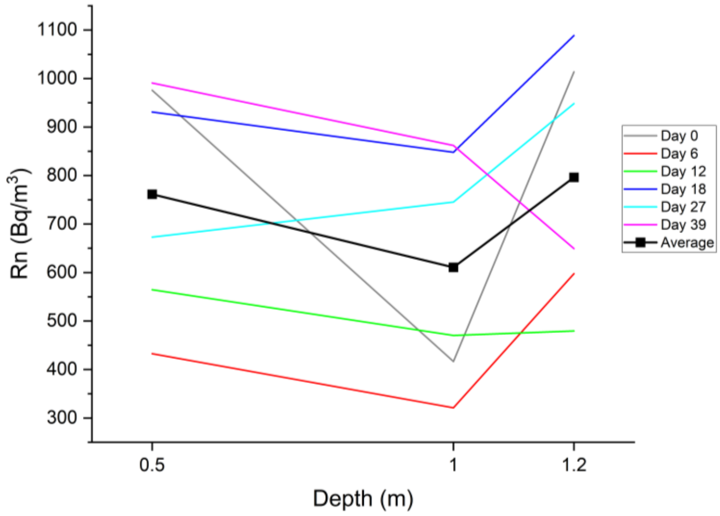

Figure 4. Radon concentration as a function of depth (0.5 m, 1.0 m, and 1.2 m) across five observation days (Day 0, 6, 12, 18, 27, and 39). The average radon concentration across depths is also plotted

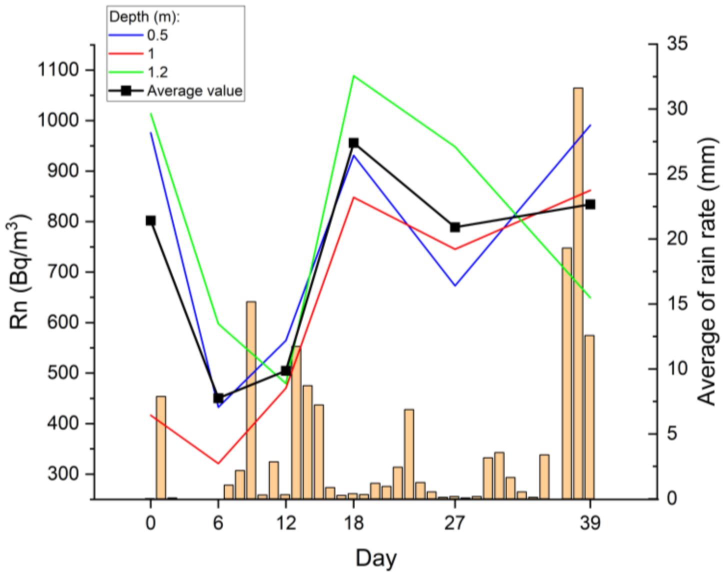

Figure 5. Radon concentration at three depths (0.5 m, 1.0 m, and 1.2 m) over time, plotted alongside the average rainfall rate (in mm) during the measurement period; The bars represent rainfall rates, while the lines show radon concentration trends

Following the peak on Day 18, radon levels begin to decline slightly, especially at 1.2 m, though they remain higher than the initial measurements. By Day 39, radon concentrations are still elevated, particularly at 0.5 m, despite significant rainfall. The elevated concentration indicates that after the soil has reached a certain level of saturation, radon may continue to escape, particularly at shallower depths, even in heavy rainfall [10], [12]. The figure demonstrates a clear "Lag Effect" between rainfall and radon concentration, with radon levels suppressed during rainy periods and spiking as the soil dries out and permeability increases [1], [5]. The rainfall may also contribute to the high CV values observed at all depths, which are 31%, 39%, and 32% for depths of 0.5 m, 1 m, and 1.2 m, respectively.

CONCLUSION

Radon concentration varies significantly with depth and time and is influenced by environmental factors like rainfall. Radon levels were highest at 1.2 m, peaking at 1,089 Bq/m³ on Day 18 and lowest on Day 6 during rainfall, suggesting soil saturation suppresses radon exhalation. Measurements at 0.5 m exhibited the lowest CV (31%), making it the most reliable depth for monitoring, balancing accuracy and practicality. This study highlights the "lag effect" between rainfall and radon release, emphasizing the importance of considering soil moisture when interpreting radon data.

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