A method for measuring the soil radon emanation coefficient without disturbing the soil structure

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Abstract

Conventional measurements of the soil radon emanation coefficient often rely on drying, grinding, or repacking, which alters the native pore structure and moisture distribution of the sample. To obtain radon emanation coefficient that is more representative of natural soils, RAD7 was used to conduct closed-loop cumulative measurements on the intact in-situ soil samples. Soil samples without structural alteration were placed in an airtight acrylic accumulation chamber, and the radon concentration in the recirculating gas loop was recorded continuously for 24 h. The radon exhalation rate was determined by nonlinear fitting of the radon concentration variation curve, and the emanation coefficient was then calculated from the exhalation rate, sample dry mass, exposed area, and Ra-226 specific activity. Three natural soil samples were used to validate the method. All samples showed a typical nonlinear accumulation pattern, with rapid early growth followed by slower increase at later times, and the fitted R 2 values ranged from 0.86 to 0.92. The radon exhalation rates were 3.04$±$0.35, 4.01 $±0.34, *and*4.69±$0.42 mBq • m -2 • s -1 , corresponding to emanation coefficients of 0.36 ± 0.04, 0.44 ± 0.04, and 0.59 ± 0.05, respectively. In the study, under the same specific activity of Ra-226, due to the differences in water content and porosity, different radon emanation coefficient were obtained. The proposed approach provides a practical basis for obtaining source-term parameters that are closer to actual field conditions for site screening, radon potential assessment, and foundation-soil evaluation.

Full Text

method

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Abstract

Conventional measurements radon emanation coefficient often drying, grinding, repacking, which alters native structure moisture distribution sample. obtain radon emanation coefficient representative natural soils, conduct closed-loop cumulative measurements intact in-situ samples. samples without structural alteration placed airtight acrylic accumulation chamber, radon concentration recirculating recorded continuously radon exhalation determined nonlinear fitting radon concentration variation curve, emanation coefficient calculated exhalation rate, sample mass, exposed area, Ra-226 specific activity.

Three natural samples validate method. samples showed typical nonlinear accumulation pattern, rapid early growth followed slower increase later times, fitted values ranged radon exhalation rates 0.35, 0.34, emanation coefficients 0.04, 0.04, respectively. study, under specific activity Ra-226, differences water content porosity, different radon emanation coefficient obtained. proposed approach provides practical basis obtaining source-term parameters closer actual field conditions screening, radon potential assessment, foundation-soil evaluation.

Keywords

Radon emanation coefficient, Undisturbed soil, Radon exhalation rate,

Closed-loop monitoring

Introduction

Rn-222 radioactive noble generated decay soils rocks transported upward through space toward ground surface World Health Organization identifies radon major indoor environmental carcinogen treats control important public-health systematic review measurements Chinese dwellings, schools, offices found strong spatial variation indoor exposure levels Case-control Gansu further increases high-exposure residential settings City-scale monitoring Zhuhai already indicated indoor radon uneven within coastal urban Because low-rise buildings exchange across foundation, realism radon-risk assessment depends ground source characterized ethodological studies therefore treated practical bridge between subsurface generation exposure assessment Early national demonstrated exhalation broad radon-prone patterns across China research showed texture related physical properties influence soil-gas concentration surface release Later national-scale estimation confirmed radon density China highly heterogeneous space Radon exhalation outward expression deeper process, parameter fraction radon atoms generated Ra-226 escape solid phase interconnected space [10].

Classic studies explicitly distinguish radon emanation coefficient surface exhalation [11]. value depends recoil, diffusion, phase partitioning grain scale rather boundary alone [12].

Reviews radon migration therefore place emanation interface between radium occurrence solids subsequent transport porous media [13].

Because parameter separates release efficiency simple source inventory, underpins geogenic radon mapping source-strength comparison [14]. sense, emanation coefficient parameter links physical state exhalation eventually observed surface [10].

Field measurements Chinese sedimentary granite terrains illustrate soils broadly comparable geological settings still yield different exhalation intensities [15].

Surveys high-background areas South China likewise subsurface radon occurrence strongly dependent [16].

Urban observations Shenzhen further indicate soil-gas radon thoron respond sensitively local near-surface conditions [17].

Recent Urumqi extended point linking indoor soil-gas radon characteristics regional radon potential [18].

Previous studies agree radon emanation coefficient fixed material label,

because changes geological setting climatic state [19].

Controlled chamber experiments showed early moisture alter emanation substantially solid source remains unchanged [20].

Japanese experiments later clarified nonlinearity response showing radon thoron release strongly water content [21].

Measurements representative Okinawan soils likewise confirmed natural soils broad range emanation coefficients [22]. recent experiments added grain size, porosity, mineralogical controls picture linking characteristics emanation diffusion [23]. factor

analysis

researchers concluded moisture, temperature, porosity, mineral composition, radium occurrence together rather independently [24]. coupling means single-factor interpretation often unstable unless structural state sample clearly defined [24].

Heating experiments loess further showed thermally induced structural change shift release behavior material [25].

Depth-resolved measurements northern Shaanxi indicated lithology burial context modify radon release patterns [26]. focused loess moisture demonstrated again water content reorganize emission behavior realistic field range [27]. broader scale, recent compilation upscaling emphasized radon-flux still reflect strong methodological environmental heterogeneity [28].

Fault-zone studies Beijing demonstrated soil-gas radon respond sharply structurally controlled degassing pathways [29].

Similar evidence Tangshan connected soil-gas radon anomalies activity seismogenic faults [30].

Measurements across Anninghe Zemuhe fault systems reached comparable

conclusion

southwestern China [31]. Degassing research along western Ordos margin likewise showed active structures modulate radon transfer depth surface [32]. outside obvious fault belts, basin-scale surveys Gansu recorded pronounced variability soil-gas radon [33].

Karst investigations southwest China further suggested special pore-fracture systems generate localized soil-radon anomalies [34].

These observations explain researchers tried estimate emanation diffusion coefficients simultaneously rather treat release simple constant [35]. parallel, one-cycle chamber

analysis

proposed accelerate exhalation measurement under controlled conditions [36].

Ventilation-type accumulation procedures introduced trace concentration growth efficiently [37].

Open-loop calculation frameworks revised reduce nonideal accumulation behavior [38].

Closed-chamber studies further improved quantitative treatment exhalation through tighter mass-balance

analysis

calibration [39]. Reference-device comparisons AlphaGUARD confirm

measurement circuit configuration still affect derived

result

[40]. Recent instrument development improved continuous monitoring radon fault zones [41]. review literature shows methodological

discussion

centered measurement procedure structural representativeness tested [10]. laboratory workflows, soils dried, crushed, sieved, repacked before testing because those operations simplify geometry reduce measurement difficulty [10]. practical difficulty emanation controlled micro-scale release, whereas experiments observe radon after already crossed chamber-scale boundary [13]. pretreatment changes route between recoil accessible therefore alter measured coefficient activity remains unchanged [12].

Drying especially sensitive because redistributes water films enhance recoil capture saturation hinder further transfer higher saturation [21].

Crushing sieving expose fresh mineral surfaces while simultaneously destroying original network through which radon migrated field [23].

Repacking creates second artificial structure defined laboratory handling rather natural state [24]. pretreatment reorganize characteristics moisture-bearing microenvironments already known influence radon release [42]. coefficient obtained disturbed material therefore describe reconstructed medium rather current release efficiency original [43]. fundamental reason values prepared samples difficult transfer directly near-surface transport models building-site assessments [14].

Field systems preserve environmental context effectively, current instruments mainly target soil-gas monitoring rather direct derivation emanation coefficient intact sample [41].

method

preserves native geometry while keeping chamber balance manageable therefore still needed [39].

Otherwise, improved precision refine behavior artificial sample rather reveal behavior place [14]. distinction crucial emanation input transport models screening [13]. unresolved problem motivates present study. collect stainless-steel cutter preserve existing structure possible, measure radon emanation coefficient relatively intact samples instead fully disturbed repacked material. strategy intended retain arrangement particles, pores, moisture-bearing microenvironments control radon release faithfully conventional pretreatment. providing coefficient closer present structural state soil,

method

should offer realistic basis

source-strength evaluation, radon transport modeling, radon-risk assessment building sites. objective study demonstrate feasibility significance measuring radon emanation coefficients ring-cutter intact sampling.

2.1 Experimental

equipment preparation experimental located unpaved natural ground surface Hengyang, Hunan Province.

Because sensitivity decreases markedly under high-humidity conditions, surface candidate points first rapidly screened digital soil-moisture meter before sampling, areas extremely moisture excluded. samples unaltered structure collected slowly uniformly pressing stainless-steel cutter inner diameter height soil, sample volume provides sufficient radioactivity counting statistics while minimizing disturbance natural connectivity during sampling.

After retrieval, bottom cutter immediately sealed sample transported laboratory, where undisturbed ambient temperature allow sampling stress release short-term exchange stabilize. drying, crushing, recompaction treatment applied samples

during the entire RAD7 monitoring stage.

advantage ring-cutter sampling geometric boundaries sample clearly defined, which facilitates incorporation exposed area, sample volume, unified calculation framework.

Compared collecting repacking container, ring-cutter samples require secondary compaction leveling during transport installation, thereby reducing opportunities artificial reconstruction structure. soils under natural conditions, integrated preservation geometry structure important simply increasing number samples, because emanation coefficient corresponds efficiency radon release existing structural state rather characteristic value fully homogenized material. measurement system consisted airtight acrylic accumulation chamber, recirculating circuit, miniature pump, drying tube, Nafion tube, temperature humidity sensors, electronic radon detector. fixed effective gas-phase space above accumulation chamber. circulation drove chamber through drying dehumidification chamber, forming closed-loop circulation.

Unlike simple static end-point measurement, closed-loop system continuously record concentration growth process without opening chamber,

thereby preserving early-stage growth information late-stage decay constraints. operated sniff mode, using signal infer concentration, improve response speed concentration changes. instrument calibrated national standard radon chamber University South China, calibration factor detection During formal measurements, single sampling cycle repeated continuously cycles, giving total

monitoring duration of 24 h.

ensure comparability among different samples, study sample geometry, exposed area, closed-loop gas-circuit configuration identical. accumulation chamber connecting pipelines checked airtightness before experiment, connecting tubes length, model drying tube, circulation setting avoid additional caused geometric differences apparatus.

Because sensitive humidity, Nafion closed lowered humidity operating range instrument helped reduce total volume closed-loop system. combining unaltered structure samples closed-loop dynamic monitoring, provided complete series subsequent full-process nonlinear fitting.

Schematic diagram apparatus measuring radon emanation

coefficient

2.2 Formula

Derivation Processing soil, undergoes alpha decay produce radon emanation coefficient denoted temporal change radon activity within particles written activity solid phase, activity, lambda decay constant reach dynamic equilibrium within particles, obtained

( ) 0 R n d A t d t = (2)

dynamic equilibrium relationship, expression releasable radon space obtained further written emanation-coefficient equation,

¢ - = = (3)

airtight accumulation chamber, radon exhalation surface exposed surface effective gas-phase volume closed chamber concentration growth process under continuous exhalation radioactive decay described time-series concentration values obtained imported Origin 2024, fitted nonlinear least squares obtain Compared

methods

linear slope initial stage accumulation, full-process fitting substantially reduce amplification random fluctuations first points.

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After completion dynamic monitoring, porosity measured volume displacement method.

Keeping cutter undisturbed sample level, purified water slowly injected until sample fully saturated, injected water volume recorded. porosity calculated according Because arranged after radon exhalation experiment, additionally interfere original measurements during radon release stage.

V V h = ´ (5)

total sample volume, i.e., volume cutter, volume water required reach saturation. sample obtained constant-weight method. sample placed stainless-steel dried continuously constant-temperature After cooling temperature, weighed, drying weighing procedures repeated until difference between consecutive measurements constant-weight criterion. specific activity measured using CIT3000F low-background gamma spectrometry system.

After monitoring, samples dried, ground, passed through sieve. sample weighed polyethylene sample sealed, ensure radioactive equilibrium between progeny Counting performed lead-shielded chamber thickness specific activity converted characteristic energy peak.

Using measured values radon emanation coefficient calculated according where dimensionless radon emanation coefficient; exposed surface area; radon exhalation rate; sample; specific activity Ra-226; decay constant Rn-222.

Because specific activities three sample groups study similar, independent effects structure moisture distribution emanation coefficient could identified clearly.

result

consider fitting overall shape concentration growth curve, consistency parameter trends.

3. Results

physical parameters three samples unaltered structure

summarized Table masses Sample Sample Sample volume sample porosity values 19.1% Sample 18.2% Sample 26.4% Sample whereas moisture contents 16.3% Sample 19.6% Sample 23.7% Sample Sample showed highest porosity moisture content, indicating relatively loose solid skeleton greater retention natural moisture pores.

Samples similar porosity, their moisture contents clearly different makes suitable analyzing moisture effect within intermediate moisture range. specific activities Sample Sample Sample maximum relative difference 3.76%. indicates subsequent differences radon accumulation mainly controlled source strength.

Because three groups samples similar source strengths different structures moisture conditions,

experiment

effectively created ideal natural-state comparison scenario. other words, different samples ultimately exhibited significantly different radon exhalation rates emanation coefficients, differences likely attributable physical state rather content itself. radon concentration series obtained continuous monitoring shown Table three samples exhibited accumulation trend rapid first slowed, gradual approach equilibrium appeared later times, indicating closed-loop system successfully captured typical nonlinear growth process jointly controlled continuous exhalation radioactive decay.

Sample concentration increased Sample

140.53 Bq

Sample Although local declines occurred periods middle later stages, around Sample around Sample these statistical fluctuations affect overall parameter trends. three sample groups Radon concentration Radon concentration Radon concentration

results

three series. three fitted curves passed through distribution range measured points, early-stage slope late-stage quasi-equilibrium features reproduced well, indicating mass-balance model based reasonably describe radon accumulation process closed-loop system study. particularly important samples unaltered structure, because structural heterogeneity natural samples often produces pronounced statistical fluctuations within single sampling cycle; first points calculate slope, short-term fluctuations easily misidentified differences exhalation rate.

Fitted radon concentration curves three samples 2-(a), 2(b), 2-(c) represent Sample Sample Sample respectively radon exhalation rates Samples 0.35, 0.34, respectively; fitted values 0.86, 0.92, 0.90, respectively; emanation coefficients 0.04, 0.04, 0.05, respectively.

Compared Sample Sample showed 54.28% increase radon exhalation 63.89% increase emanation coefficient, indicating under combined action porosity moisture content, recoil radon enter Sample moisture content higher, emanation coefficient still increased 0.44, indicating within natural moisture range study, moisture effect offset small structural differences.

shorter half-life therefore measured curves truly reach ultimate equilibrium concentration strict sense.

However, because simultaneously incorporates continuous source decay constraint, fitting still yielded stable exhalation-rate estimates. low-to-high ranking parameters among different samples entirely consistent trends moisture content porosity, internal consistency strengthens credibility results. perspective combined parameter relationships, comparison between Samples reflects independent moisture, because their porosities similar whereas their moisture contents differ; comparison between Samples strongly reflects superimposed enhancement structure moisture. other words, within ranges sample moisture content porosity study, thin-water-film effect associated increasing moisture content first promoted increase emanation coefficient, porosity further increased, growth additionally amplified better gas-phase connectivity.

4. Discussion

emanation coefficients obtained study overall higher representative value commonly cited review Sakoda [10], inconsistent observations Markkanen Arvela, Furbish, Bossew moderate moisture contents significantly enhance emanation capacity [11,44,45].

Hosoda found experiments radon thoron emanation increasing moisture content first promotes suppresses release [21].

Huynh further pointed soils different particle-size fractions, emanation coefficient rapidly approach stable value within certain moisture range [23]. moisture contents three samples study concentrated between 16.3% 23.7%, which precisely within range where water films promote escape recoil radon while pores excessively blocked water, relatively reasonable emanation coefficients obtained clear physical basis. perspective medium structure,

results

study mutually corroborative existing knowledge different soils fractured media China.

Studies soils different lithologies northern Shaanxi structures northern China shown proportion micropores, contact relationships among mineral particles, weathering features related depth jointly alter radon release pathways [26,46].

Results

thermally treated loess indicate particle-surface conditions reorganization significantly rearrange exhalation rates [25].

Two-dimensional fracture

models fractal discrete fracture network models further fracture connectivity enhanced, radon migration further amplified [47,48].

Sample present study highest porosity highest moisture content, therefore ranked highest among three parameters, which consistent structural

control mechanisms described above.

undisturbed-soil measurement strategy direct implications engineering practice.

Regional radon potential assessment often requires rapid comparisons across large number sites, whereas radon-protection design building sites requires parameters close possible actual foundation-soil conditions. standard parameters obtained dried reconstructed samples used, laboratory repeatability improved, release capacity natural soils moderate moisture content underestimated.

Conversely, relies entirely instantaneous soil-gas concentration,

results

easily affected meteorological conditions boundary disturbances.

method

proposed between these approaches: preserves repeatability controlled indoor measurements while establishing direct connection between

results

natural field structure. potential application scenarios present

method

limited ordinary soils. Studies temperature dependence radon diffusion coefficient porous media shown transport parameters coupled temperature humidity, empirical values obtained under single standard condition become difficult extrapolate [49]. studies heap-leached uranium columns, red-clay-bentonite cover layers, anomalous radon sources underground spaces, researchers likewise found small changes material structure, moisture boundary, source occurrence state significant shifts exhalation behavior [50,51,52]. latest occurrence modes sandstone-type uranium further indicates that, under similar source strengths, differences distribution positions radionuclides within mineral particles radon release efficiency [53].

Furthermore, environmental interpretation emanation coefficient cannot separated scale conditions. macroscopic scale, actual migration radon indoor space controlled foundation cracks, pressure differences, surface cover, seasonal changes moisture.

Therefore, parameters obtained study cannot mechanically equated indoor radon concentration itself.

Nevertheless, level source identification, screening, relative comparison among different soils, emanation coefficient obtained after preserving undisturbed structure remains irreplaceably valuable, because provides robust input parameter linking indoor

intrusion models actual radon exhalation capacity soils.

Measurements unaltered structure improve interpretability parameter comparisons among different sites.

method

proposed combined future standardized sampling depth, unified indoor/outdoor environmental records, GIS-based geological-unit databases, possible build spatial distribution emanation coefficient remain experimentally repeatable while being closer actual surface conditions. databases could serve identifying high-radon areas, providing refined source-term inputs underground-space development, ventilation design underground engineering works, performance evaluation ecological cover layers. comparison three sample groups similar specific activities study another important implication: demonstrates source-strength differences compressed,

method

still stably resolve differences radon release. investigations, difficult question whether contains radium, which locations prone supplying radon upward under similar source-term backgrounds.

Although number samples study limited,

results

variations moisture content porosity sufficient cause significantly different emanation coefficients, which means discriminative sensitivity

method

practical value for engineering screening.

study still belongs methodological validation preliminary application.

Although undisturbed structure maintained during sampling monitoring stages, particle-size distributions, mineral composition, specific surface area, soil-gas profile obtained simultaneously, relative contributions moisture content, porosity, mineralogical factors could quantitatively separated.

Although monitoring sufficient support exhalation-rate fitting, longer series replicate samples still required stability lower-activity samples under seasonal freezing-drying-wetting cycles.

Future should therefore carry repeated experiments across types, seasons, wider moisture gradients, should integrate analyses within soil-gas flux, indoor intrusion risk, regional radon potential assessment, establish practical parameter database balances realism, repeatability, engineering utility.

5. Conclusions

study presents practical

method

estimating radon emanation coefficient

natural-state soils while preserving their original structure moisture distribution. combining ring-cutter intact sampling, closed-loop monitoring, full-curve nonlinear fitting,

method

reduces introduced drying, crushing, repacking therefore yields parameters closer actual near-surface conditions. three samples similar Ra-226 specific activities, concentration curves described satisfactorily accumulation model, fitted values radon exhalation rates 0.35, 0.34, emanation coefficients 0.04, 0.04, respectively.

Under comparable source-strength conditions, parameters increased Sample Sample indicating higher moisture content greater connectivity enhanced radon release efficiency tested natural soils.

These

results

preserving undisturbed state important evaluate relative release capability rather behavior artificially reconstructed sample. proposed

method

therefore suitable screening, comparison natural soils, provision source-term parameters radon potential assessment foundation-soil evaluation.

Because present remains preliminary validation based limited number samples, further testing across types, moisture ranges, seasonal conditions still needed before broader empirical relationships established.

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