Management of Radon in Tunnel Drilling

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Abstract: According to the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) report in 1982, radiation from radon contributes about 50% of all natural radiation sources to the public. The situation is worse in Hong Kong where large area is granitic containing larger amount of uranium when compared to the global mean. Radon level can therefore be on the high side during tunneling especially where poor ventilation is envisaged. This article includes realistic field study of radon in tunnel under construction. A maximum concentration of over 30,000 $\mathrm{Bq/m^3}$ was recorded (1 Becquerels per cubic meter is equivalent to 0.027 pico Curies/L). Radon concentration in tunnel environment is found to be related to groundwater ingress, ventilation provision and geology. A review of the current statutory control in Hong Kong is done as well as its comparison with other countries' practices. In fact, the situation can be improved through education, adopting control legislation and more specifically, having a suggested radon management plan in every tunnel drilling project.

DOI: 10.1061/(ASCE)0733-9364(2004)130:5(699)

CE Database subject headings: Radon; Tunnels; Drilling; Ventilation.

Introduction and Background

The lung cancer risk for underground operatives due to the inhalation of natural radon is well documented (Akerblam 1982). Radon (having chemical symbol Rn) is a naturally occurring, colorless, odorless, almost chemically inert, heavy, radioactive gas (Cothern and Smith 1987). One of the significant properties of radon is its relatively high solubility in water that accounts for its presence at substantial amounts in groundwater and spring water. Chemically, there are 27 known isotopes of radomn, only Rn-222 is called radon in practice and is studied. Other isotopes like Rn-219 is called actinon and Rn-220 is called thoron because they are originated (decayed) from actinium series and thorium series. Radon (Rn-222) comes from the uranium series and its path of decay is shown in Fig. 1. Various measurement methods of radon and its daughters have been identified and used. Most of them are measuring the ionization energy released during the radioactive decay. For radon gas concentration measurement, continuous radon monitoring electronic devices are frequently used in Hong Kong. Air is pumped into a counting chamber which is typically a scintillation cell or ionization chamber. Scintillation counts are processed by electronics, and radon concentrations are stored in the instrument's memory or directly transmitted to a printer.

Health risk caused by radon has long been realized. Radon and their principal daughters, polonium, lead, and bismuth, emit alpha particles which are highly ionizing. Lung tissues can be damaged and this can lead to lung cancer. Besides, the health hazard causes by radon exposure is stochastic, i.e., the effect whose probability of manifestation increases with the dosage but there is no threshold of exposure below which it is certain that the effect will not occur. The radon and its decay products in both "attached" (on the dust and suspended particle) and "unattached" (free aerosol) forms are delivered to sensitive tissue in the human respiratory system when the radon-rich air is inhaled. The situation is worse in Hong Kong because the granitic rock is containing larger amount of uranium at 93 Bq/kg (Yu et al. 1992) than in other countries where the global mean is of 26 Bq/kg (UNSCEAR 1982). Microscopically, the biological damage by radon comes from the ionizing radiation as this involves the formation of free radicals. These are extremely reactive and react with other molecules such as deoxyribose nucleaic acid causing chromosomal aberrations. Biological damage to cells, tissues, and whole organisms may involve immediate death of cells, cell modification leading to mutation, or mitotic damage or reproductive death, and hence the formation cancer tissue.

Radon Hazard in Tunnel Drilling

Hong Kong is a highly developed metropolitan region where technical and economic developments have made it possible to support 6.3 million people on only about 1,100 $\mathrm{km^2}$ of built-up land. This gives rise to a large number of underground structures. Besides the precious and scarce developed land, the unique characteristics of mountainous terrain in Hong Kong also give rise to the opportunity and prospect of tunneling which linked up various structures without occupying valuable land area. Tunnels have been constructed for various purposes including water supply, sewage drainage, railway, vehicular traffic, and electricity supply (McFeat-Smith 2000).

In general there are two main methods for hard rock tunnelling

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Note. Discussion open until March 1, 2005. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on January 29, 2003; approved on September 3, 2003. This paper is part of the ***Journal of Construction Engineering and Management***, Vol. 130, No. 5, October 1, 2004. ©ASCE, ISSN 0733-9364/2004/5-699–707/$18.00.

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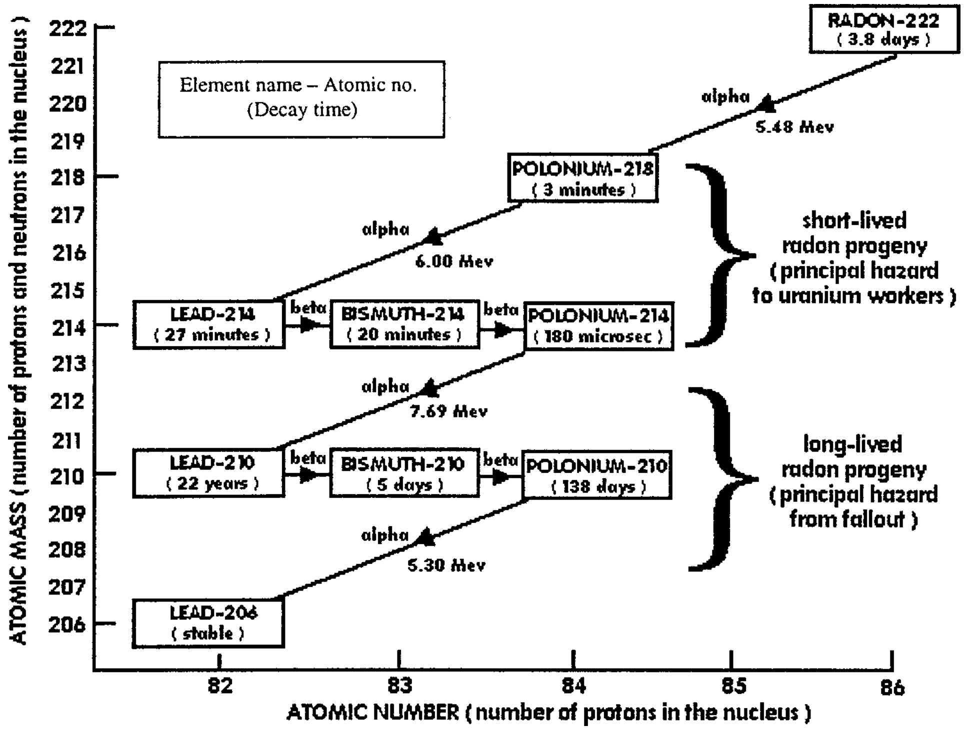

Fig. 1. Decay of radon in uranium series

which are frequently used in Hong Kong. They are the excavations of tunnel by drill and blast (D&B) and tunnel boring machine (TBM). Another technique called the pipe jacking is also used in Hong Kong for short length tunneling. Drill and blast has been the traditional and most commonly used method of excavating tunnels in hard rock geology like Hong Kong. The TBM, on the other hand, has its increasing importance in Hong Kong tunneling works. The main advantage of TBM is that the process is noncyclic, allowing excavation proceeds concurrently with disposal of rock. This gives a higher rate of excavation than traditional cyclic methods. There is also less disturbance to the rock resulting in minimal temporary support and virtually no overbreak, thus giving advantages where a full permanent lining is required. However, the main disadvantages of TBMs are the lead time required before the start of excavation and high plant costs which can be proportionally overridden when the total length of tunnel drive is long enough (see Figs. 2–7).

Radon Exposure in Tunnelling Environment

Radon is naturally decayed from uranium which is a natural mineral contained in rocks and soils. The content of uranium varies in different rocks as well as different area. Tunneling is simply hole drilling on rock underground or across a mountain. When the rock is disturbed, the large surface areas of newly born rock crevices and fissures are where the radon emits.

There is limited literature about radon exposure on tunneling. However, the radon exposure risk among miners has been well published (International Commission on Radiological Protection 1981; Lam et al. 1988). Yu and Stokes (1991), based on a relative risk model, estimated the number of radon induced lung cancer deaths per year in Hong Kong to be 280. However, the tunnel workers have not been included. Since the study is based on the average radon exposure by the general public which can be much lower than those by the tunnel workers, radon induced cancer risk for this specific high exposure group of people could only be higher.

Regulations and Standards for Controlling Radon Exposure

In view of the increased cancer risk that inhalation of radon can bring about, various standards and limits on safe exposure have been developed. However, the statutory limit of radon exposure in different countries is not the same.

The International Commission on Radiological Protection (ICRP), the World Health Organization and the International Atomic Energy Agency have encouraged countries to develop programes on radon. Countries have been encouraged to issue advisory levels for radon in workplaces, issue guidelines, and introduce limits. In Europe, the European Commission (EC) issues Council Directive 96/29/EURATOM for laying down basic safety standards for the protection of the health of workers as well as the general public against the dangers arising from ionizing radiation, a requirement for monitoring of radon and corrective measures against exposure to radon in the workplace (European Community 1997).

The ICRP presents a series of recommendations for action levels in workplaces as well as in residential dwelling (International Commission on Radiation Protection 1993). The document treats workers who are not regarded as being occupationally exposed to radiation as members of the public. It is then logical to adopt an action level for intervention in workplaces at the same level of effective dose as the action level for residential dwellings. The action level for intervention in workplaces can be rounded as $500-1{,}500\ \mathrm{Bq/m^3}$. When selecting action level for dwelling and workplaces, authorities should choose values that are similarly located within the ranges.

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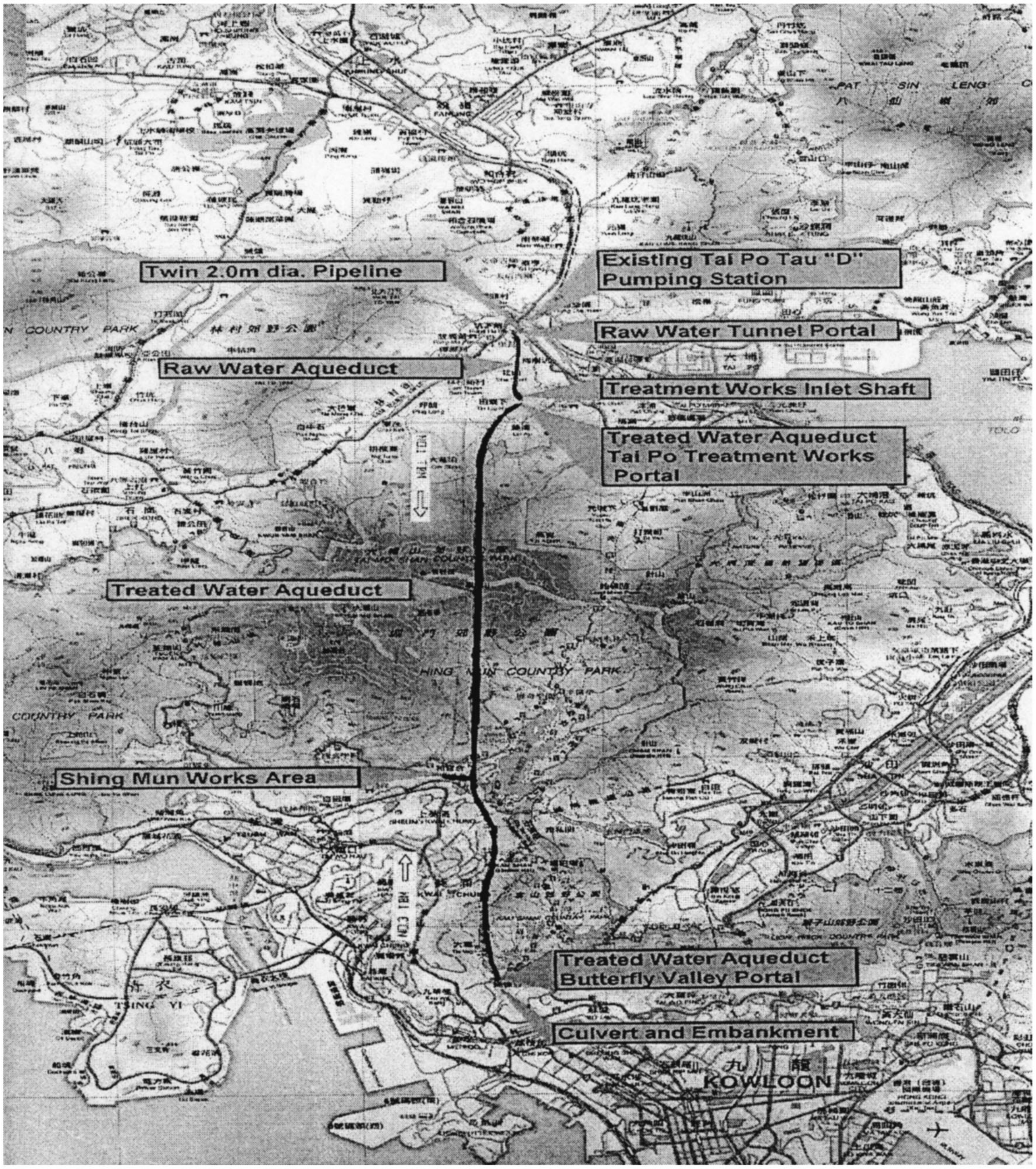

Fig. 2. Location plan for tunnel drilling for raw and treated water aqueduct

To echo the EC council directives, many European countries have set up comprehensive standards and guidelines about occupational radon exposure limit. However it is found that many countries do not have a standard for underground works. In some countries, like France, even if an occupational exposure limit is set, it is limited to buildings open to the public and schools. Moreover, for those countries where both standards are equipped, the limits set for the residential dwellings are usually lower, i.e., more stringent than the occupational limit. The reason may be based on the assumption that the time a person spent in the residential dwelling is longer than those in workplaces. However, as mentioned in ICRP 65, it is logical to adopt an action level for intervention in workplaces at the same level of effective dose as the action level for dwellings.

Of the European Union member states, the range of radon levels implemented by all responding countries is 200–3000 Bq/m^3, which differs from the ICRP recommendations. Countries have often implemented different reference levels for different types of workplaces. In fact, the ICRP recommendation provides guidance for national authorities in setting up their own limits. Different countries may differ from each other in geological aspect, technical competence, and social view in the radon hazard. Besides, the risk for radon induced lung cancer can also be different for different people in different countries as a result of epidemiological study. Countries should base their criteria on their own epidemiological data for workers and geological investigation to develop standards for tunnel workers.

Radon Management in Hong Kong

Concerning the health hazard of the tunnel operative due to excessive exposure to radon, the responsible department in Hong

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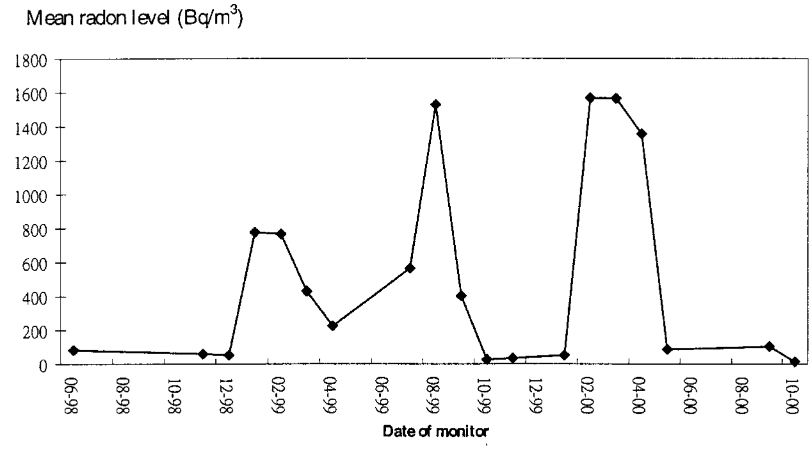

Fig. 3. Records of mean radon concentration in treated water aqueduct (Tai Po-Shing Mun)

Kong is Labor Department. The Occupational Hygiene Division under the Labor Department is responsible for controlling and monitoring the environmental condition inside the tunnel so as to maintain a safe and healthy workplace for the tunnel operatives.

Regarding the legislative control, Hong Kong does not have specific legislation for controlling occupational radon exposure. General provision can be found in the Occupational Safety and Health Ordinance and the Factories and Industrial Undertaking Ordinance. These pieces of legislation in Hong Kong that protect tunnel operatives' excessive exposure to radon are administered by the Labor Department. The General Duties provisions of the Occupational Safety and Health Ordinance and Clause (6A) of the Factories and Industrial Undertaking Ordinance require the person responsible to ensure, so far as reasonably practical, the safety and health of all the workers at work. It is well known that radon concentration in an enclosed space is related to the degree of ventilation provided. The Occupational Safety and Health Regulation requires that the person responsible for a workplace ensures that the workplace is adequately ventilated by fresh air and that, as far as reasonably practicable, the air within the workplace be kept free of impurities. The Construction Sites (Safety) Regulations also require the contractor responsible for the work to take all reasonable steps necessary to prevent the inhalation of dust and fumes generated at work. These general duties and ventilation provision requirement require the employers and contractors to take measures to protect the workers from excessive exposure to radon and its daughters in a tunnel. In terms of enforcement, Occupational Safety Officers will normally require radon measurement to be taken. They will have site visits occasionally to ensure that radon concentration inside the tunnel is within the safety limit. There is no specific limiting value published. However, it is known that in the enforcement, the Labor Department will make reference to the recommendations on radon exposure made by the ICRP which had been mentioned in previous sections.

Unlike other countries in the world, Hong Kong does not have a specific provision in the legislation for control of occupational radon exposure. Concerning radon exposure hazard by tunnel operatives and underground workers, there are not even guidelines, standards, and code of practices published by the authorities telling the industries how radon is managed and what value of radon concentration should be maintained to safeguard the health of the tunnel operatives. The Labor Department may, when considered as part of the safety issue during the site visit, require something to be done on radon. However, without a clear legislation, standards, and guidelines, the control becomes confusing and unconvincing. In Hong Kong tunneling projects, monitoring of radon is not a statutory compulsory activity. Without specific limit for the industries to comply, management of radon hazard becomes a voluntary activity. If in one project, radon management is in-

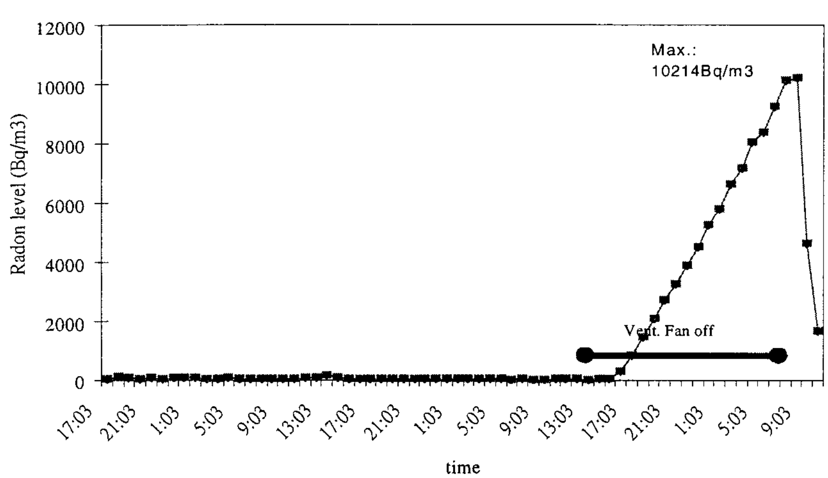

Fig. 4. Mean radon level when tunnel ventilation is turned off (incident 1: Tai Po to Shing Mun)

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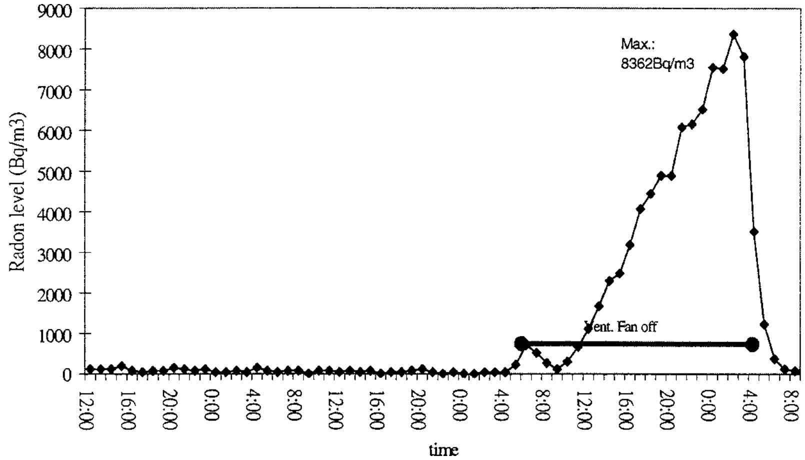

Fig. 5. Mean radon level when tunnel ventilation fan is turned off (incident 2: Tai Po Tau)

cluded in the contract document between the client and the contractors, measuring activities and action plans may be carried out at the client's expense.

Compared with the rest of the world, the rate of lung cancer in Hong Kong's people is very high (see Table 1). Although high lung cancer statistics do not directly imply a higher radon hazard, excessive radon exposure can always be a possible cause. Moreover, when compared with the United Kingdom and Canada, even if the lung cancer incidence rate is lower than Hong Kong, a governmental control over occupational radon exposure is equipped.

Case Study in Tai Po to Butterfly Valley Aqueduct in Hong Kong

As stated in the previous sections, there is limited literature regarding the risk of occupational radon exposure, especially for tunnel operatives. This invisible fatal risk seems to create less attention in the industries than it ought to. A case study on one of the tunneling projects in Hong Kong is conducted to review the actual situation.

The project was part of a major new water treatment and transfer scheme by the Water Supplies Department in order to meet the increasing demands for water supply. The complete project comprises a 1.2 kmlong, 3.8 m diameter raw water aqueduct; a water treatment plant in Tai Po; a 12.1 km long, 3.8 m diameter treated water aqueduct and a primary service reservoir in Butterfly Valley. In particular, the whole 12.1 km long treated water aqueduct, which transfers treated water from Tai Po to Butterfly Valley near Lai Chi Kok, was constructed underground and involved the use of D&B and TBM in its tunneling works. The aqueduct construction was commenced in 1997 and completed in 1999.

In the Tai Po aqueduct construction, a consultant environmental team carried out radon measurement inside the tunnel on a scheduled basis from June 1998 to October 2000. The measurement was done by using RAD7. Continuous measurement for a 2 day duration will be each time of monitoring. The result of radon concentration in Bq/m^3 for Tai Po to Shing Mun Treated Water Aqueduct is summarized as follows. For the tunnel, more than one measurement had been taken for each recorded month. Results of the mean radon level are calculated on a per day basis and the highest and lowest radon concentration recorded is also stated.

It can be seen that the radon concentration recorded for the aqueduct during construction ranges from 13 Bq/m^3, which is a relatively low level on October 2000 to over 1,500 Bq/m^3 on August 1999, February 2000, and March 2000. From the graph showing the mean radon level inside the tunnel, it can be seen that

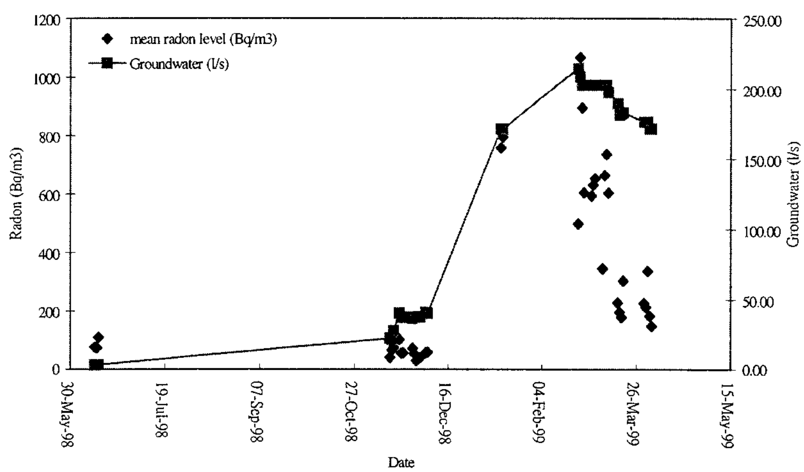

Fig. 6. Groundwater ingress and mean radon measurement in treated water aqueduct

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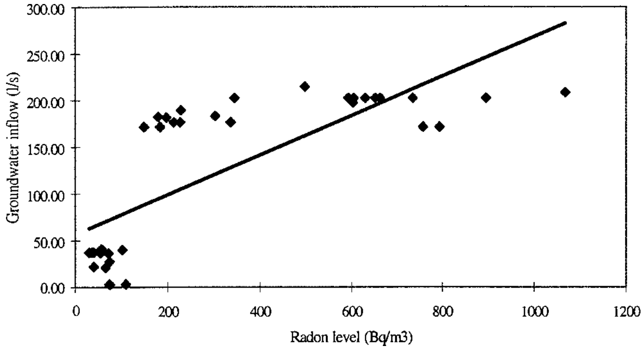

Fig. 7. Correlation between groundwater ingress and mean radon measurement in treated water aqueduct between Tai Po and Shing Mun

the radon level does not show any particular trend. Since the radon level recorded was in the construction phase of the tunnel with continuous tunnel drill proceeding and measurement was taken at various work faces of the tunnel, a traditional die-out curve is not expected. Conventionally, radon concentration in structure is expected to fall with time. As the tunnel drilling goes on, a number of environmental factors change. The radon level inside may vary with these changes. Some factors expected to have influences on radon emission were investigated in the following sections.

Besides the mean radon level showing the average radon concentration in the tunnel each month, it can be seen that the radon level surges up to over 10,000 Bq/m^3 on November 1998, nearly 20,000 Bq/m^3 on August 1999 and September 1999, and over 30,000 Bq/m^3 on July 1999. These levels of radon concentration are unacceptable when compared to any safety standards around the world. The main reason for these high radon surge incidents was due to the malfunctioning of the ventilation system. The ventilation system may not be efficiently maintained when some tunnel fans break down or when power breaks down. Regarding the lowest level recorded, it seems to have no minimum value for

Table 1. Lung Cancer Statistics in Different Countries (Source: Hong Kong Cancer Fund)[a]

Country/City	Males	Females
China, Qidong	35.0	11.0
China, Shanghai	56.1	18.2
China, Tianjin	55.9	37.0
Hong Kong	74.7	30.7
Japan, Osaka	43.5	12.4
Singapore		
Chinese	62.7	19.6
Indian	14.3	3.5
Malay	37.2	9.6
Australia, New South Wales	46.6	14.9
Canada	65.4	28.0
United Kingdom, England and Wales	62.4	22.8
United States, Los Angeles		
Black	88.7	35.4
Chinese	36.5	16.4
Non-Hispanic White	59.7	38.6

[a]World age-standardized incidence rate (per 100,000) for selected countries, 1998–1992.

radon gas concentration in the tunnel. Negligible radon concentration is recorded elsewhere. Therefore, with effective management, maintaining a very low level of radon during tunnel construction and so a safeguard of the health of the tunnel operatives is not impossible.

In general, when looking at the mean, highest, and lowest radon level, the worst months seem to occur during late 1999 and early 2000. When compared with the program of the tunnel construction, these are when the boring works were finished. Construction works were mainly on the tunnel lining which involved welding works and grouting works. From the records obtained, there is no evidence that tunnel boring will increase the radon level significantly.

Analysis of Radon Level in Tunnel Drilling

Ventilation

The objective of ventilation in any tunnel is to provide fresh air for the establishment of an acceptable environment. In Hong Kong, ventilation provision in tunnel works is a statutory requirement under the Occupational Safety and Health Regulation. There are no figures for fresh air supplies at minimum threshold. It should be noted that the quantity of fresh air supplied to a tunnel is usually determined not by breathing requirements but by the necessity of diluting pollutants and cooling purposes.

In The Tai Po Aqueduct project, the ventilation is provided conforming to the British Standards BS6164 Code of Practice for Safety in tunneling in the construction industry. It provides guidelines for the fresh air requirement inside the tunnel, i.e., $9\ m^3/(\min\ m^2)$ of tunnel section. Additional supplies of $2.5\ m^3/\min$ per working brake horse power are recommended where the plant is used.

The tunnel is constructed by two numbers of TBM drilling together at both ends. Before the tunnel was drilled through, ventilation was provided by fans at both ends. Fresh air was blown into the tunnels at the tunnel portals creating positive pressure inside. Exhaust air was naturally bled off by the positive pressure back to the tunnel portals and vented to the atmosphere. After the tunnel was drilled through, a longitudinal ventilation system was adopted. Besides fans at the tunnel portals, axial jet fans are installed inside the tunnels along its length to boost the air flow. Tai Po portal was used as the air intake and the portal at the Butterfly Valley is used as the exhaust end.

During the tunnel construction period, occasional ventilation system breakdowns occurred. Effective ventilation is a prime for mitigating radon accumulation. Radon emission continuously occurs at the tunnel rock. Fresh air is provided to the inside of the tunnel to prevent the accumulation of radon gas. Radon rich air was then exhausted to the atmosphere and quickly dispersed by wind. Two incidents are selected to show how radon concentration surged up when the tunnel ventilation system broke down. The two incidents occurred at different times and at different places but both of them show the relations between ventilation and radon concentration in the tunnel.

Groundwater Ingress

The Tai Po Treated Water Aqueduct construction was characterized by its high groundwater ingress when compared to other

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tunnel projects in Hong Kong (McFeat-Smith 2000). Relatively high levels of radon were recorded during the periods where high water ingress was observed.

Just as uranium is present in all rocks and soils, so are radon and radium, because they are daughter products formed by the radioactive decay of uranium. Each atom of radium decays by ejecting from its nucleus an alpha particle composed of two neutrons and two protons. As the alpha particle is ejected, the newly formed radon atom recoils in the opposite direction. Alpha recoil is the most important factor affecting the release of radon from mineral grains.

The recoil of the radon atom is quite strong. Often newly formed radon atoms enter the pore space, cross all the way through the pore space, and become embedded in nearby mineral grains. If water is present in the pore space, however, the moving radon atom shows very quickly and is more likely to stay in water filling the pore space. Since radon is soluble in water, it will remain in the water having a much higher mobility than the rock and soil. The groundwater then carries the radon and flow underneath by gravity. As a result, it is suspected that the level of radon inside the tunnel during construction is positively related to the groundwater infiltration rate.

Groundwater infiltration varies throughout the tunnel construction period. Data of groundwater infiltration was recorded from June 1998 to June 1999 and plotted below together with the radon concentration measured. It can be seen clearly that both peaked in early 1999. It can be seen that groundwater plays an important role in radon emission during tunnel construction.

A significant correlation is found between groundwater inflow into the tunnel and the radon level recorded. The correlation coefficient (r) is found to be 0.764 and an R square value of 0.583 was found. Therefore, it can be concluded that the radon concentration inside a tunnel is positively correlated with the groundwater inflow. In other words, a groundwater flooding incident can be an early warning to the radon surge.

Geology

In the Tai Po Aqueduct Project, geological information was also available early in the design stage. The Geotechnical Engineering Office under the Civil Engineering Department has published geological map showing the rock type in different areas in Hong Kong. This is valuable information as the long Tai Po Aqueduct passes through different rocks during different construction periods. An investigation has been done to determine if there is any relation between radon emission and drilling against particular rocks.

The geological maps indicated that the treated water tunnel would intersect the following rock types: granodiorite, volcanic rock of Tai Mo Shan Formation, volcanic rock of the Shing Mun Formation, granodiorite again, fine-grained granite, medium-grained granite, and coarse-grained granite, together with many minor intrusive dyke rocks. For the purpose of radon analysis, three major types of rocks are considered and they are granodiorite, granite, and tuff. The radon level recorded at different locations of the tunnel at about the same period of time is mapped with these type of rocks. A two tailed t-test assuming nonequivalent variances with a significant level of 0.05 is performed. It can be seen from the hypothesis testing that for tunnel with granitic rocks, a significantly higher radon level is recorded when compared with the granodiorite rocks and tuff. The reason may be due to the relatively higher radium content in granitic rocks in relation to the others. Since geological study will be done in advance of every tunnel drilling and a relatively high radon emission is envisaged when drilling against granitic rocks, special attention to radon management is advised when the tunnel drilling is on granitic rocks in Hong Kong.

Discussion

The case study at Tai Po Aqueduct revealed the potential radon hazard in the tunnel construction project. It gives an idea on the significance of the radon issue. It is noted that radon concentration can surge up to over 30,000 Bq/m^3, a level which far exceeded any safety limit in the world. With unique characteristics where tunneling plays an important role in the development of Hong Kong and as many as several thousand construction workers in a year working underground in tunneling, particular attention should be paid to this invisible radon hazard.

From the study, it can be seen that a lack of ventilation for a short period of time can lead to a significant rise in radon level being measured. Ventilation is therefore vital to maintain the radon concentration within an acceptable limit. Besides, particular attention should be paid to the effectiveness of fresh air change and to radon gas removal at the work face. In general, mechanical ventilation was provided in tunnels under construction by extraction or by excess pressure with or without air duct using fans. However, in long tunnels like those in the case study, experiences show that apparently these methods by themselves might not provide sufficient ventilation at the work face. One directional air flow propelled by jet tunnel fans should be incorporated

The other important factor which may affect the radon concentration in tunnels is groundwater ingress. Radon can be transported through groundwater to the tunnels. The groundwater infiltration and radon concentration also shows a significant correlation to each other. Although radon gas is invisible, odorless, and cannot be detected naturally, groundwater ingress is easily noticeable in the tunnel. Therefore when high groundwater ingress is found during tunneling, attention should be paid to the possible build up of radon gas.

In the study, it is also shown that radon emission is especially significant when tunneling is done on granitic rock in Hong Kong. Therefore, measures such as increasing the frequency of monitoring, improving the ventilation system, etc. should be taken when tunnels are drilled through granitic rock.

Finally, the analysis aims to highlight some environmental factors that are correlated to radon emission. It should not be misinterpreted that at low groundwater and tunnel drilling through rocks other than granite, the radon issue can be ignored. Since radon hazard is fatal, every effort should be done to ensure a safe working environment for the tunnel operatives.

Radon Management Plan for Tunnel Drilling

Based on the findings of the various policies and surveys of common practices, a radon management plan for use in Hong Kong is proposed.

Design Stage

Actions to be taken before the project commenced should include:

1. Study on the geology of the ground being drilled, where particular attention should be paid on granitic rocks. If the whole tunnel or sections of the tunnel are drilled through

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granitic rocks, radon hazard during the construction period is expected to be higher. For more precise result, material analysis on the rocks can be carried out. The uranium and radium content in the rocks is highly influential on the radon emission.

2. Conduct borehole investigation on the ground water levels at different sections of the proposed tunnels. When groundwater infiltration is expected to be high at sections where high groundwater head is envisaged, radon hazard for such sections is also expected to be higher.
3. Deciding the standards and limits being adopted. In dealing with a health hazard, radon limits should be set as low as possible. However, since radon gas emission is a natural and continuous process inside a tunnel, a value as low as outdoor concentration is not practical in an enclosed space. The Tai Po Aqueduct experience shows that radon concentration of 1,000 Bq/m^3 is maintainable. Moreover, factors like geological characteristics and expected groundwater inflow should be considered in deciding such radon limiting value. In all cases, the value recommended by the ICRP (4.8 WLM) should not be exceeded.
4. Include radon management in the specification of the contract. In Hong Kong, since legislation is not specific, radon management responsibilities should be clearly indicated in the contract document. In specifying radon management, requirements like standards adopted, measurement method and equipment, frequency or schedule of monitoring, locations of monitoring, and approciate actions when action level is exceeded should be clearly stated. Otherwise, the radon management may not be enforceable.
5. Carefully design tunnel ventilation system. In Hong Kong, guidelines on BS6164 regarding the fresh air requirement are normally adopted. However, the effectiveness of radon gas removal depends on the efficiency of the ventilation system.

Action Plan During Project Period—Management of Workers

Radon hazard is stochastic and its health risk is progressively related to the time of exposure. In order to safeguard the health of the tunnel operatives, radon exposure time should be limited. In general, workers can be exposed to low radon concentration for a long time while short time exposure should be limited to high radon concentration. For example, in order to follow the ICRP's 4.8 WLM recommendations, a worker, if exposed to a potential alpha energy of 1 WL (correspond to 3,700 Bq/m^3 radon activity concentration in equilibrium), the annual working time inside such an environment should be limited to 4.8 months. On the other hand, if a worker is required to work continuously inside a tunnel of 12 months per year, the potential alpha energy should be maintained at 0.4 WL (correspond to 1,480 Bq/m^3 radon activity concentration in equilibrium).

From this rationale, the health risk of the tunnel operatives can be protected by a duty rotation system. First, record the working time for each or each group of tunnel operatives. Second, monitor and record the radon concentration inside the tunnel. Then, the radon exposure for each or each group of tunnel operatives can be calculated. Finally, the annual total exposure for the tunnel operatives can be limited to a preset value by rotating their duty roster with those working outside the tunnel. The advantage for this system is that it does not hinder project progress while safeguarding the health of the tunnel operatives. However, the drawback is that it may not be applicable in some specialized duties which cannot be substituted by others. The nonproportional distribution of the workers inside the tunnel to those working outside may also be a constraint to this duty rotation system.

Contingency Plan for Radon Gas Management

A contingency plan is an essential component in radon gas management for tunnel drilling. As seen from the Tai Po Aqueduct project, incidents like ventilation fan breakdown, power breakdown, and high groundwater ingress can lead to a surge in radon concentration inside the tunnel. Actions to be taken in a time of a radon surge should be carefully planned. When tunnel length is too long for the plan to be implemented, one should divide the tunnel into different sections and implement the plan at each section of the tunnel independently.

1. Divide the preset or specified value of radon concentration to be maintained throughout the project into three levels and parts. Set the trigger level, action level, and target level in precedence. For example, if 1,500 Bq/m^3 is specified to be maintained, the trigger level will be 500 Bq/m^3, the action level will be 1,000 Bq/m^3, and the target level will be 1,500 Bq/m^3.
2. Conduct weekly monitoring of radon concentration inside the tunnel and record the findings.
3. Follow any contingency plan if the trigger level is recorded.

Measurement Outside Tunnels

For decades, ventilation is the most effective way to mitigate radon hazard inside tunnels. Through proper ventilation, radon gas is diluted and exhausted. Just as in preventing the radon accumulation and creating equilibrium, the concentration of radon can be greatly reduced. However, when radon-rich air is continuously extracted out of the tunnels, the area nearby may also be affected. In theory, natural atmospheric dispersion can maintain the radon concentration near the tunnel portals at a low level. The effectiveness depends on the arrangement of the area and the atmospheric condition varying from time to time. If the tunnel portals are surrounded by high-rise buildings or mountains, which make dispersion ineffective, radon hazards may not lessen in outdoor conditions (Man and Yeung 1998). Therefore, particular attention should also be paid to monitoring the radon concentration at the tunnel portals.

Conclusions

To be complete, environmental management should consider the harmful effect from nature. It is well known that radon hazard is invisible but fatal. However, the issue has not been seriously addressed until recent years. Although significant numbers of research works have been done to investigate the nature of radon, its health effect on the human body and its level of significance in the built environment, limited literature regarding the natural radon emission in the tunnel and its health hazard to the tunnel operatives are available. It has been shown, by the Tai Po case study, that the problem is more severe than expected.

In Hong Kong, the characteristic of high granite composition of soil and rock and the extensive use of the tunnel make the issue more significant. However, the government has not placed sufficient emphasis on this issue when compared to other countries. This is reflected by the lack of specific legislation for control and guidelines or code of practices on the subject. The responsibility

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to protect the health of tunnel operatives seems to have fallen on the individual project manager who has overall control of the project. However, due to a lack of education and control, industries do not seem to have sufficient knowledge to handle the situation.

In the study, it is shown that radon concentration in the tunnel is strongly related to ventilation, groundwater ingress, and geology. The effect may vary in different situations but it helps the planners to decide what should be taken into account in drafting a radon management plan. Moreover, the plan should at least include continuous monitoring of radon concentration, a worker management system, a contingency plan, and outdoors portal measurement.

Last but definitely not least, epidemiological study should be conducted for setting up radon exposure limits for tunnel operatives in Hong Kong and education programs should be launched to raise the public awareness. In front of the cost of human lives, no effort should be spared in setting up a comprehensive management regime for the radon challenge.

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