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Development and test of a combined radon sub-slab suction and sub-slab drainage system

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Development and test of a combined radon sub-slab suction and sub-slab drainage system

B H Høegh[1], T Hansen[1] and S Clausen[1]

[1] Danish Technological Institute, Gregersensvej, DK-2630 Taastrup, Denmark
E-mail: brh@teknologisk.dk

Abstract. To ensure a healthy indoor environment, the indoor air level of the radioactive gas radon must be kept low according to the WHO. This can be achieved by installing a radon sub-slab suction system. In buildings with a basement at the same time a sub-slab drainage system is often necessary. This paper describes results from a project, aiming to combine a radon sub-slab suction system with a sub-slab drainage system. A combined system will minimize the number of pipes when constructing new buildings and will also provide an easier retrofitting method for adding a radon sub-slab suction system to buildings with an existing sub-slab drainage system. In the project, it was found that the combination of the two functionalities required an airtight system to lower the pressure under the ground slab, an unhampered drainage of ground water and a prevention of odour from the drains. To meet these requirements, a prototype of a well with a water trap, a water outlet and a separate suction pipe for the air outlet was developed. A low voltage fan was installed in the suction pipe. The system was installed in a detached house with a 104 m^2 basement. After installation, the pressure reduction over the ground slab in the basement was measured to be able to investigate the effect of the suction system independently of the radon exposure. The results showed a reduction of the pressure in the farthest corners under the ground slab by approximately 0.6 to 1.9 Pa compared to the pressure over the ground slab. We concluded that a combined radon sub-slab suction and sub-slab drainage system is possible with the designed well, although the use of a stronger fan will be necessary to meet the identified test objective of pressure reduction $\Delta P \geq$ 1-3 Pa.

1. Introduction

To reduce the risk of lung cancer, the WHO recommends an average indoor radon level under 100 Bq/m³, while a level of 300 Bq/m³ should not be exceeded [1]. In Denmark, where this project was conducted, since 2010 an average indoor radon level under 100 Bq/m³ is suggested for buildings established before 2010, while this level is mandatory for buildings established later than 2010 [2]. There are three concepts to control the radon level in the indoor air [1] [3] [4]. 1) Increased ventilation can reduce the radon concentration by diluting the indoor air with outdoor air, as the latter has a radon content of approximately 5 Bq/m³ [4]. 2) Barriers and membranes aim to seal the constructions adjacent to the ground, and thus to stop the transport of radon into the indoor environment. 3) Reducing the pressure under the ground slab, e.g. by sub-slab suction systems, which reverses the flow of soil gas, amongst others radon, and thus prevents radon from entering the building. Reducing the pressure under the ground slab is considered the most effective measure to control radon in the indoor air [5].

In Denmark, the radon concentration in the ground generally lies between 5,000 and 50,000 Bq/m³, locally up to 100,000 Bq/m³ [6]. According to a nationwide investigation in Denmark, the soil type is the most important factor influencing the indoor radon level. The risk of radon levels over 100 Bq/m³ in the indoor air is higher for buildings, placed on moraine clay than for buildings placed on shifting sand [7]. Coincidentally, buildings with a basement placed in clay soil normally need a drain, to remove the infiltrated water from the basement constructions. While the Danish Building regulations in those cases recommend a perimeter drain [2], the sewer contractor, who was part of the project, additionally recommends a sub-slab drainage system to ensure a dry ground slab. For houses with basements, placed on moraine clay, there thus is a high risk of a coincidence of the need to control radon in the indoor air and to ensure dry basement constructions.

The project, that is subject of this paper, aimed at solving these two issues in one installation by using the drainage pipes under the ground-floor for both sub-slab drainage and radon sub-slab suction. A combined function would minimize the use of pipes in new constructions. Additionally, the aim was to enable an easy retrofit – without the need of taking the ground slab up – of a radon suction system in buildings with an existing sub-slab drainage system.

2. Requirements of a combined system

Initially, the requirements of a combined system were identified, based on the requirements for and experiences with the separate installation of the systems.

Radon sub-slab suction systems are based on lowering the pressure under the ground slab to prevent soil gas from infiltrating the indoor air through the ground slab. A pressure reduction over the ground slab of 1-3 Pa will be necessary, as this is the amount, that the indoor air pressure is lower, than the outdoor air pressure because of thermal buoyancy in the heating season [4]. For lowering the pressure, an airtight but porous suction zone under the ground slab is needed. Porous materials, as for example pebbles, shingles, coated lightweight expanded clay aggregate and gravel are normally used as capillary layer under a ground-slab. For a suction layer of gravel, [4] mentions a pressure reduction of 100 Pa in the suction point to be sufficient to disperse the pressure reduction to the outmost corners of a detached house, which results in a reduction of the indoor radon level of 75 % to 95 %. Thus, by radon sub-slab suction indoor radon levels of 400-1,000 Bq/m^3 can be reduced to the relevant limit of 100 Bq/m^3. A Danish nationwide investigation of indoor radon levels in 348 detached houses shows average radon concentrations of 10-560 Bq/m^3 [6]. A total removal of radon from the indoor air is not possible, as the outdoor radon concentration in Denmark is approximately 5 Bq/m^3, and an indoor background radon concentration of 10-20 Bq/m^3 has to be expected [8]. To ensure that the pressure reduction is dispersed under the whole building, it is important to reduce intrusion of false air into the suction layer. According to [4] a pressure reduction of 100 Pa typically can be established by a fan with a size of 15-150 W and a capacity of 10-300 m^3/h. The sewer contractor requested a low voltage fan, as a 220 V installation in the sewers will require higher security level for the electrical installations. Furthermore, the fan should be silent, to avoid noise pollution.

For sub-slab drainage systems, the drainage pipes are placed in the capillary layer under the ground slab [9] [10]. In the combined system of radon sub-slab suction and sub-slab drainage (further on called RSWD-system), the drainage pipes should be used as suction pipes, thus they should both transport water and air. When connecting a sub-slab drainage system to the drains system in Denmark, it will, in concern to future cloudbursts, as a rule be necessary to pump the drain water into the drains system [9]. Thus, a sand trap chamber and a pump chamber are required between the sub-slab drainage system and the drains system. Preferably, the drained water should be dispersed to a rainwater system. But if a separate system is not available, it could be dispersed to a combined drains system, [9]. In that case the pressure reduction in the RSWD-system should not result in accidentally sucking air from the drains system, especially from a combined drains system, to avoid obnoxious smell leaking into the atmosphere.

3. Method of control of the combined system

The control of radon mitigation methods will normally be based on measurements of the indoor radon concentration. The significance of such measurements is though dependent on the radon level in the ground and in the indoor air. In addition, radon measurements have to comply with certain rules concerning their duration and the time of the year, in which they are conducted. Partly because indoor radon levels are higher in the heating season, due to thermal buoyancy of the heated indoor air and due to reduced air change rates in the heating season. Partly because the indoor radon concentration is varying significantly over time. Thus, according to Danish recommendations measurements to estimate the mean year value of the indoor radon level have to be foretaken over minimum 60 days and in the heating period, that is from October 1st to April 30th [8]. As this control method is very time consuming and requires a test site with high radon levels, a different control method was chosen.

To examine the effect of the RSWD-system, the achievable pressure lowering under the ground slab should be controlled. If the pressure under the ground slab in the outmost corners of the building could be lowered by 1 to 3 Pa compared to the indoor air pressure, the RSWD-system would be considered effective enough, to ensure an indoor radon level under the in Denmark required 100 Bq/m^3, provided that no other significant radon sources contribute to the indoor climate. This leads to the test objective noted in equation (1).

$$\Delta P \geq 1\text{-}3 \text{ Pa} \quad \text{with} \quad \Delta P = P_{\text{indoor air}} - P_{\text{soil air}} \tag{1}$$

4. Development and 1:1 installation of a combined system

The combined system – the RSWD-system –was developed to meet the above-mentioned requirements, to ensure unhampered water drainage and sufficient pressure lowering in the suction zone under the ground slab. The developed RSWD-system was installed at a test site, a typical brick house from the 1939 with a 104 m^2 basement, whose original ground slab was to be replaced by a 100 mm reinforced concrete ground slab placed on 300 mm rigid insulation and a 100 mm capillary layer. The developed RSWD-system consisted of the suction chamber and the layer for water drainage with the piping, a well for both water dispersion and pressure reduction, a fan to establish the pressure reduction and measurement points to control the function of the system.

4.1. The suction chamber and the layer for water drainage with the piping

The suction chamber was formed by the foundations of the external walls, the new ground slab and the ground. Coated lightweight expanded clay aggregate 10 to 20 mm was, because of its good porosity, used as capillary material, as layer for water drainage and suction zone. The RSWD-pipes were installed corresponding to the installation of a traditional sub-slab drainage system by placing drainage pipes in the capillary layer with a slope of minimum 3 ‰ preferably 5 ‰ [9] towards the outflow. The pipe routing is, among others, illustrated in Figure 1.

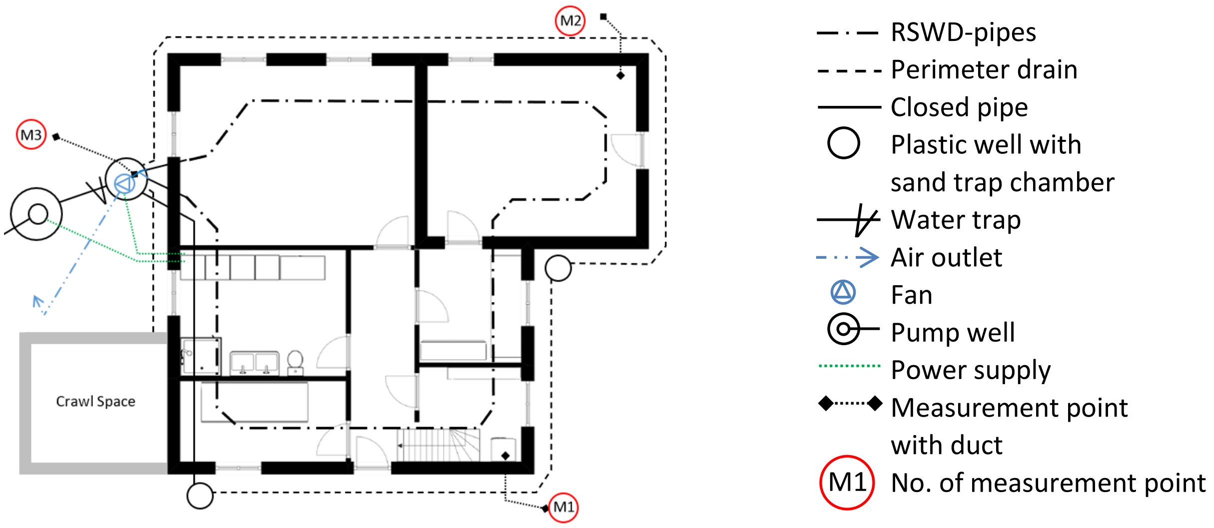

Figure 1. Basement floor plan of the case building, showing the pipe routing of the RSWD-system and the ordinary perimeter drain, the wells with sand trap chambers, the fan and the measurement points.

As internal partition wall foundations divided the suction chamber in smaller sections, the drainage pipes were run, so they passed through all these chambers. 300 mm on the inside of the foundations the pipe material was changed to closed pipes. The pipe penetrations through the foundation of the external wall were sealed with suitable rubber cuffs to prevent intrusion of false air. The suction chamber was additionally tightened by sealing the joint between the ground slab and the walls – both the external and the internal partition walls, – with an elastic sealant. In addition, suitable rubber cuffs or elastic sealant were used for house service connections, e.g. for fresh water and electricity. The closed RSWD-pipes were then passed into a plastic well with suitable airtight rubber cuffs.

4.2. The well for both water dispersion and pressure reduction

The core of the RSWD-system was a 425 mm plastic well, – called the RSWD-well – that combined both water dispersion and pressure reduction and contained a water trap, a sand trap chamber and the suction point for pressure reduction, see Figure 2. The incoming closed pipes of the RSWD-system were split into a water pipe downwards and a suction pipe upwards. The water pipe dispersed the water through a water trap into the sand trap chamber. According to [9] a water trap has to have a height of minimum 70 mm, which is equal to 70 bar or to 686 Pa (1 bar = 9.8067 Pa). Thus, the water trap assessed to withstand the target pressure reduction in the suction point of 100 Pa, to enable the planned pressure reduction for the radon sub-slab suction function and to avoid obnoxious smell being sucked out of the drains system. In the suction pipe a fan was installed for pressure reduction in the RSWD-system. Two types of fan installation were tested. In one case, the fan was connected to both ends of the RSWD-pipes, see Figure 2 (b). In the other case, the fan was connected to only one end of the RSWD-pipes, see Figure 2 (c). The suction pipe was led out of the well with a suitable airtight rubber cuff. The air outlet was formed as a gooseneck and placed at a location, that prevented radon in accidentally seeping from the air outlet into the indoor air through e.g. an open window. At the test site the outflow from the RSWD-well was connected to the available combined drains system via a pump well, to ensure proper diversion of the drain water. The location of the wells is illustrated in Figure 1.

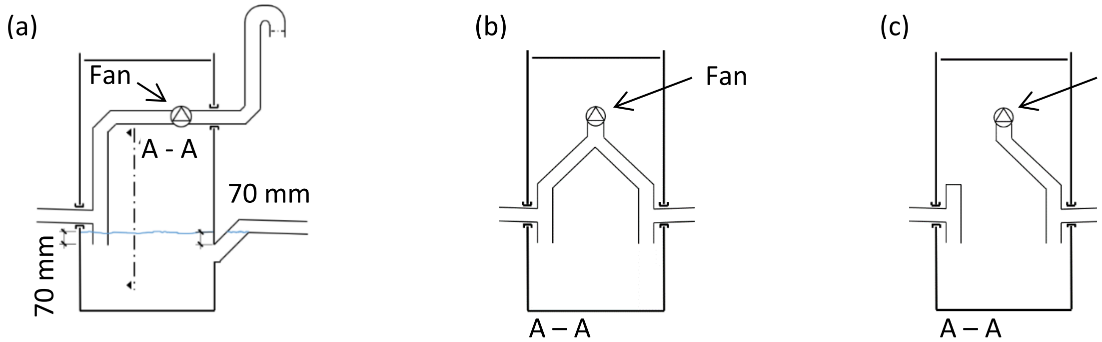

Figure 2. Principle sketch of (a) the RSWD-well with water trap, sand trap chamber, fan suction point and air outlet. Section A-A showing the splitting of the pipes with the fan attached to (b) the end of both incoming suction pipes and (c) the end of only one of the incoming suction pipes.

4.3. The fan

To establish the pressure reduction over the ground slab a fan was installed in the suction pipe. As the in Denmark available standard fans are optimized for air flow and not for pressure reduction, it was difficult to find a suitable fan. At last, a low voltage inline blower for small boat engine room ventilation of type *In-line Blower 12 V, Biltema (Art. 25-839)*, was chosen, because this kind of fans are small and used in surroundings with high relative humidity. However, the request of a silent fan could not be fulfilled. Furthermore, the documentation of the fan was poor, specifying an electricity consumption of 2.5 A and a maximum airflow of 3.6 m³/min, equivalent to 216 m³/h. To get an idea of the possible pressure reduction, that could be established by the chosen fan, a simple test was conducted. The inline blower was installed at the end of a 2 m closed pipe sealed with a cap at the end. Running the inline blower at maximum power, it could establish a pressure reduction in the pipe of 260 Pa. The inline blower was installed in the RSWD-well, so that it could be detached and lifted for service and flushing of the RSWD-system. Furthermore, a stepless regulation of the fan was installed in the basement of the test site.

4.4. Measurement points
Three measurement points to control the pressure difference over the ground slab were planned, as shown in Figure 1. The two measurement points (M1 and M2) were placed in the outmost corners of the building and one measurement point (M3) should be placed close to the suction point. Unfortunately, measurement point (M3) was not established at the test site.

The measurement points were placed next to a plastic well with a sand trap chamber. A closed pipe with a diameter of 32 mm was led through the foundations approximately 100 to 300 mm into the capillary layer. The pipe penetration was sealed with a suitable airtight rubber cuff. This closed pipe was run inside the plastic well to 200 mm under the well cover. The pipe was sealed with a detachable cap. The pressure reduction over the ground slab could then be measured, sending a small plastic house down the measurement pipe to the capillary layer and another plastic house inside the basement through a sealed opening, e.g. at a window. For the measurement of the pressure reduction over the ground slab a pressure meter of the type VelociCalc Model 9555, TSI, was connected to the two houses.

5. Results
After the installation of the RSWD-system, the pressure over the ground slab in the basement was measured to investigate the effect of the suction system. The first measurements of pressure reduction over the ground slab were conducted, when the new ground slab was casted, and the house service connections and the joints between the ground slab and the walls were sealed. However, not all openings in the outer walls of the basement were closed yet, e.g. one window was missing. This resulted in unstable pressure measurements, obviously because of the winds massive influence on the air pressure in the basement, and thus on the pressure reduction over the ground slab. To solve this problem, unintended openings in the outer wall of the basement were sealed with plastic foil or elastic sealant during the following, regular measurements.

Table 1. Pressure reduction ΔP over the ground slab. Negative measures show lower pressure under the ground slab than in the indoor air.

Measurement point	M1			M2		
Speed of fan	High	Half	Low	High	Half	Low
mm/dd/yyyy	[Pa]	[Pa]	[Pa]	[Pa]	[Pa]	[Pa]
	Fan attached to both ends of the incoming RSWD-pipes as shown in Figure 2 (b)					
4/24/2019 [a]	1.7 ~ 2.1	-0.3 ~ -0.1	-1.9 ~ -1.6	0.8 ~ 1.5		-1.5 ~ -1.2
5/7/2019 [a]	1.0 ~ 1.5					
8/7/2019 [b]	1.7 ~ 1.9	1.0		0.6 ~ 1.0	-0.1 ~ 0.2	
	Fan attached to one end of the incoming RSWD-pipes as shown in Figure 2 (c)					
5/7/2019 [a]	0.5 ~ 0.9					
8/7/2019 [b]	1.3 ~ 1.6	-1.1 ~ 0.7		0.3 ~ 0.8	-0.2 ~ 0.1	

[a] Air outlet ca. 4 m after the fan, though without gooseneck
[b] Air outlet ca. 4 m after the fan through a gooseneck

Then the pressure difference over the ground slab, ΔP, was measured under different conditions: 1) Different stages of completion of the air outlet – without and with gooseneck installed. 2) Different regulations of the inline blower – full, half and low speed. 3) Different attachment of the fan – to both or to only one end of the incoming RSWD-pipes as shown in Figure 2 (b) and (c) respectively. The results of the measurements are compiled in Table 1.

Comparing the results of April 24th and July 5th, the pressure reduction over the ground slab was varying, although the degree of completion was the same. With the fan at full speed, a pressure reduction over the ground slab was measured, this was not always the case with the fan on half or low speed. In the final installation, with the gooseneck attached, the fan at highest speed and both ends of the incoming RSWD-pipes attached to the fan, a pressure reduction over the ground slab of between 0.6 to 1.9 Pa in the two measurement points M1 and M2 was measured. Under the same conditions, but the fan only attached to one end of the incoming RSWD-pipes, the pressure reduction over the ground slab was measured to be up to 0.3 Pa less.

6. Discussion

To develop a new combined system for radon sub-slab suction and water drainage – further on called the RSWD-system, – relevant literature was reviewed to identify the requirements of a combined system. Based on these requirements, a RSWD-system was developed, se Figure 1 and Figure 2, and installed at a test-site for control measurements.

To ensure the required water drainage of the RSWD-system, a sub-slab drainage system was designed after the common Danish recommendations for such systems, with drainage pipes – the RSWD-pipes. These pipes and the capillary layer represented at the same time the suction chamber, that allowed the necessary pressure reduction over the ground slab to effectively prevent the radon containing soil gas to seep into the indoor air. Coated lightweight expanded clay aggregate 10 to 20 mm was chosen as capillary material, as literature indicates that a pressure reduction of 100 Pa in the suction point of a capillary layer could distribute the necessary pressure reduction over the ground slab of ≥ 1-3 Pa to the outmost corners of a detached house, if the capillary layer had a porosity of gravel or better. To distribute the pressure reduction under the whole building, the RSWD-pipes were run through all chambers, that were formed by the foundations of the building, and the suction chamber was air tightened at all joints and lead-ins. The RSWD-pipes were, independently of the perimeter drain, led into a well, in which the separate dispersion of the radon containing soil gas and the drainage water was solved by splitting the incoming RSWD-pipes into 1) the water pipes, dispersing the water through a sand trap chamber with a 70 mm water trap, which was assessed to sufficiently withstand the pressure reduction in the suction chamber and thus avoiding obnoxious smell to be sucked out of the drains system, and 2) the suction pipes, that were led outside the RSWD-well with a gooseneck as air outlet. This arrangement was simple but effective and enabled an installation, without requiring an airtight well. For electrical safety reasons a low voltage fan was used for pressure reduction in the RSWD-system. As the fans pressure reduction was not specified, a simple test was conducted, that showed a maximum pressure reduction of 260 Pa in a closed pipe.

The effect of the RSWD-system should be investigated independently of the test sites radon exposure and by instantaneous measurements. For this purpose, pressure reduction measurements were used instead of measurements of the radon level indoor. The system would be considered effective enough to ensure an indoor radon level under 100 Bq/m^3, if a pressure reduction over the ground slab of $\Delta P \geq$ 1-3 Pa could be proved in the outmost corners of the building. Therefore, measurement points were established in the capillary layer. Unfortunately, the measurement point near the suction point had not been established, but the two measurement points farthest away from the suction point were installed. The onsite tests showed that valid control measurements only could be conducted under two conditions: 1) The ground slab and the sealed joints with other building components were established. 2) The basement was as airtight, as expected for the final construction.

Measurements showed a pressure lowering under the ground slab compared to the pressure over the ground slab; thus the suction chamber assessed to be established sufficient airtight and the overall objective with the RSWD-system was achieved. However, there were registered variations in the pressure reduction over the ground slab when measuring on different days with different weather conditions. In addition, the pressure reduction over the ground slab was up to 0.3 Pa less with the fan attached to only one end of the incoming RSWD-pipes, compared to the fan being attached to both pipes, as depicted in Figure 2 (c) and (b) respectively. Measurements in the final installation, with the fan at highest speed and both ends of the incoming RSWD-pipes attached to the fan, a pressure reduction over the ground slab of 0.6 to 1.9 Pa was measured in the outmost corners of the building. Thus, the measured pressure reduction over the ground slab was slightly less than the objective of the control measurements of $\Delta P \geq$ 1-3 Pa. Thus, a pressure reduction of more than 100 Pa in the suction point seems to be required to thoroughly fulfil the test objective.

From a practical point of view some matters were pointed out under the operation of the 1:1 installation: 1) Before the ground slab is casted, the installation of all measurement points, the correct installation of the RSWD-pipes and the air tightness of their lead-ins have to be controlled. 2) Placing the inline blower in the 425 mm RSWD-well provided challenges, as the chosen well was small. Detaching and lifting the inline blower for service and flushing of the RSWD-system was quite difficult. 3) The residents assessed the noise level of the fan to be unacceptable at high speed, but tolerable at half speed. 4) The chosen low voltage ventilator had a short lifetime.

7. Conclusions

In Denmark, for houses with basements placed on moraine clay, a coincidence of the need to control radon in the indoor air and to ensure dry basement constructions by drainage is very likely. Average indoor radon levels up to 560 Bq/m^3 are confirmed in a nationwide Danish investigation. According to literature, radon sub-slab suction systems can reduce the indoor radon level by 75 % to 95 %, if they lower the pressure under the ground slab in corners of the building by 1-3 Pa compared to the air pressure over the ground slab, provided that no other significant radon source contributes to the indoor climate. By such a reduction, indoor radon levels of 400-1,000 Bq/m^3 can be reduced to the relevant limit of 100 Bq/m^3, which covers the range of the confirmed average indoor radon levels in Denmark.

It is possible to combine radon suction and water drainage under the ground slab of the basement of a detached house in one system, which here is called RSWD-system. For this purpose, the RSWD-system has to be constructed as a closed pipe-system with openings inside the foundations, which outlines the suction chamber. The RSWD-pipes may thus not be connected with the perimeter drain. The capillary layer around the RSWD-pipes has to be chosen with good porosity, for distribution of the pressure reduction to all corners of the suction chamber. Additionally, the ground slab an alle lead-ins to the capillary layer have to be airtight, to avoid intrusion of false air to the system. In the RSWD-well, the water drainage and the air outlet for the suction system were separated without the necessity of an airtight well. At the same time a water trap could ensure, that the pressure reduction in the radon suction system could be established, and that no air with obnoxious smell was sucked out of the drains system. To establish the pressure reduction, a low voltage fan was installed in the suction pipes, which however had a short lifetime. The reason for this was assessed to be the 24-hour operation and the use of a fan, that is optimized for air flow, not for pressure reduction.

To be able to instantaneously verify the effect of the RSWD-system independently of the test sites radon exposure and time-consuming measurements of the radon level indoor, measurements of the pressure reduction over the ground slab were used. For this purpose measurement points were installed in the outmost corners of the capillary layer. Unfortunately, a measurement point close to the suction point had not been installed. Thus, it is recommended to control all components under the ground slab before casting the new ground slab, especially the air tightness of lead-ins and the installation of the planned measurement points.

Measurements in the final installation showed a pressure reduction over the ground slab of 0.6 to 1.9 Pa in the outmost corners of the building, which is slightly lower than the test objective. This led to the conclusion, that a combination of a radon sub-slab suction system and a sub-slab drainage system generally is possible. Moreover, a retrofitting of the system in buildings with an existing sub-slab drainage system assesses to be possible, provided that the existing suction chamber is sufficient airtight or can be air tightened.

Furthermore, an instantaneous control of the installed RSWD-system assesses to be possible. However, a pressure reduction over the ground slab, that does not thoroughly comply with the test objective, allows a minor amount of soil air to leak into the indoor air. Dependent on the radon concentration in the soil air, this will result in a higher indoor radon level, than the approximately 20-30 Bq/m^3, that are mentioned as the minimum in Danish buildings, but possibly still lower than the in Denmark required 100 Bq/m^3 in the indoor air. To finally determine the effect of the RSWD-system in specific locations, a measurement of the estimated average indoor radon level in compliance with the applicable recommendations, has to be conducted.

In addition, various recommendations can be given, based on the outcomes of the project:
- Special attention should be paid on the airtightness of the lead-ins through the foundations and the installation of all measurement points, before casting the ground slab.
- The effect and the lifetime of the fan should be improved, by designing a fan, that is optimized for pressure reduction, and which is silent. In case of using a fan with a significantly greater pressure reduction, the height of the water trap should be reconsidered, to avoid obnoxious smell being sucked out of the drains systems.
- The chosen plastic well for the RSWD-well was small. A bigger well, or the installation of the fan in a separate well would improve the serviceability of the system.

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