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Hygrothermal simulations of thermally insulated basement envelopes - Importance of boundary conditions below grade

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ABSTRACT

Hygrothermal simulations are widely used to predict and optimise the hygrothermal performances of building envelopes. For the walls and floors in basements, however, determining the variation of the exterior hygrothermal boundary conditions below grade are challenging due to the various and complex heat and moisture loads and the large area needed to simulate the surrounding ground. A scoping literature review is conducted to provide an overview of current state-of-the-art methods for the addressing of these boundaries. Ten of the most comprehensive studies are selected and scrutinised. The review shows that there is a lack of thorough validation for hygrothermal simulations of basements using full-scale physical measurements. The most valuable experiences from studies with somewhat different perspectives are identified. Key uncertainties include the soil's varying composition and moisture content, liquid uptake at the soil surface and transfer of precipitation, and computational costs. Finally, the review highlights the need for a recognised method/procedure to determine the exterior boundary conditions for hygrothermal simulations of basement envelopes, which can account for the varying influencing factors of the ground. Not only can a better understanding and prediction of heat and moisture performance of basement envelopes contribute to improving building durability and energy efficiency; it can also potentially result in significant economic savings, as expensive repairs below grade can be avoided or delayed.

1. Introduction

In many Nordic countries, basements comprise a significant share of the building volume. Historically, they have been important for the storage of food, owing to low summer temperatures and moderate winter temperatures. Nevertheless, the usage and design of basements has changed significantly in recent decades. Nowadays, especially in dense areas, it is desired to inhabit and use the basement space like the rest of the house. The regulatory requirements for energy efficiency, moisture control, and indoor climate control in basements are, therefore, becoming much stricter. The requirements lead to increased thicknesses of thermal insulation layers in basement walls and floors. Barrier layers and membranes (moisture, air, radon [1]) are also seeing more widespread adoption and stricter requirements. The recommended thicknesses, positions, and uses of such layers, however, differ between cold climate countries [2]. New innovative materials and products have also entered the market. Concepts are proposed to provide an increased drying capacity for basement walls [3]. A standardised approach for evaluating and comparing these performance and risk reduction measures, however, appears to be lacking.

Moisture from precipitation and snowmelt, along with the high relative humidity (RH) of the soil/backfill, inflicts a large moisture strain on basement envelopes. The ability of structures to dry outwards is also limited as compared to structures above ground, owing to the presence of the ground. Much moisture can potentially accumulate in basement envelopes wetted by leakages or flood, envelopes with insufficient drainage, poorly designed envelopes, or in newly built structures. Without the ability to dry, this moisture can lead to mould growth, bad smells, decay, and efflorescence [4,5]. Large amounts of moisture can also gradually accumulate in the thermal insulation used below grade when exposed to moisture over time [6,7], significantly reducing the thermal conductivity [8], and thus the overall thermal performance of the basement envelope.

In the field of building physics, hygrothermal simulations are widely used to predict the hygrothermal performances of building materials, components, and entire buildings. However, as described by many

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authors [9–12], a large number of hygrothermal tools are currently available. At least 57 different hygrothermal numerical tools existed in 2013 (14 generally available) [9]. The tools vary in their degrees of mathematical sophistication and runtime requirements i.e. based on different mathematical models (physical descriptions), use different driving potentials, and utilise different numerical methods for the space and time discretisation. Accordingly, the tools have different potentialities, strengths and weaknesses, e.g. the ability to include air transfer [13], 2D or 3D phenomena [14], or the ability to simulate a high number of zones in a reasonable execution time. Selecting the tool best suitable for a specific problem can thus be challenging. For basement envelopes, another challenge is to adequately determine the exterior boundary conditions below grade. Essentially, the contact with the ground distinguishes the basement envelope parts from those building components solely above grade (i.e. exterior walls and roof), see Figure 1. For exterior walls and roofs, much research has been conducted on the development of numerical models and validation with experimental data [15] and the determination of exterior and interior boundary conditions [16–19].

Adequately determining the exterior boundary conditions below grade is more challenging because the conditions; (1) varies along with the height below grade, (2) depends on soils' varying hygrothermal properties, composition, moisture content and freeze/thaw, (3) depends on the thermal resistance of the envelope and the indoor temperature, (4) depends on the exterior climate including solar radiation, shading, precipitation, snow cover, and (5) are affected by the height of the ground water table. According to EN 15026:2007 [18] a RH of 99% can be assumed for the ground surrounding buildings, however, to the authors' knowledge, no recognised methods/procedures exist to determine the exterior boundary conditions for hygrothermal simulations of basement envelopes. The heat loss from buildings to the ground has been investigated by many authors (e,g. [20]) and can be calculated according to NS-EN ISO 13370:2017 [21]. The methodology, however, aims at assessing the energy performance, and its simplifications might not be optimal for predicting the exterior hygrothermal boundary conditions of basement envelopes. Geving et al. [22] used a two-step approach to perform 2D hygrothermal simulations of a basement envelope retrofit. First, temperature variations along the exterior side of the envelope below grade was determined by heat transfer simulations of the envelope and surrounding ground. Second, the temperature variations along with the exterior surface of the envelope were used as boundary conditions in the hygrothermal simulations along with a RH of 98%. Geving et al. [22] included a large part of the ground in the heat transfer simulations, however, constant soil thermal properties for saturated soil was used.

The inadequacy of existing simulation tools to replicate actual conditions below grade results in great uncertainty concerning the suitability of risk reduction methods for basement envelopes. As an example, simulations performed by Geving et al. [22] indicate that using vapor permeable thermal insulation on the exterior side of the basement walls, in cold climates, increases the outwards drying rate of the basement wall and results in dryer wall at equilibrium. However, the potential drying effect is strongly dependent on the temperature on the exterior side of the exterior insulation below grade. Using a constant (high) soil thermal conductivity and neglecting solar radiation and snow cover results in a conservative estimate for the heat loss and risk of condensation within the basement wall during winter. The outwards drying rate below grade, on the other hand, is overestimated because it

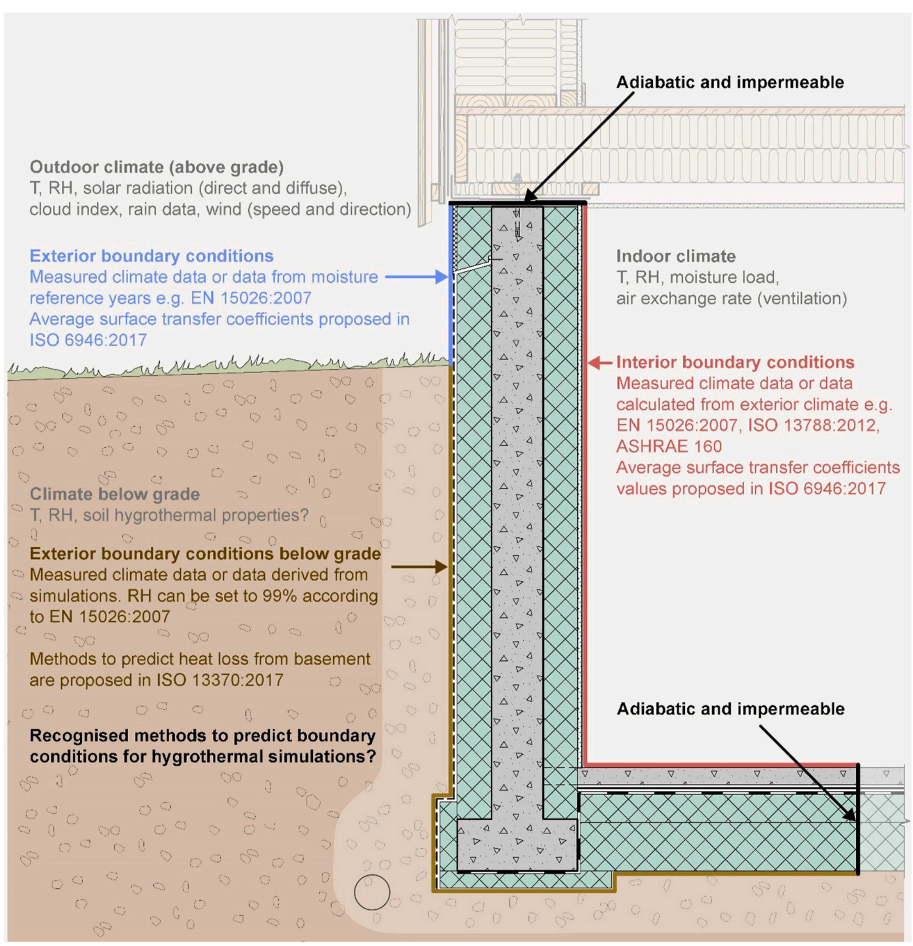

Fig. 1. Interior and exterior boundary conditions required for simulations of basement envelopes.

increases with decreasing temperatures. Inwards moisture flow due to solar radiation are also underestimated. A more thorough assessment of the exterior boundary conditions, considering different locations/climates, soil compositions and effects of moisture transfer would aid in providing more accurate assessment of the suitability of various risk reduction measures.

This paper seeks to investigate the current methodology of determining boundary conditions below grade for hygrothermal simulations of thermally insulated basement envelopes. The main objectives of this study were to (1) identify studies concerning the hygrothermal performance of basement envelopes, (2) investigate the methods, numerical tools, assumptions, simplifications, and exterior boundary conditions used below grade in these studies, (3) investigate how such simulations have been validated with measurements, and (4) identify valuable experiences for improving hygrothermal numerical simulations of thermally insulated basements.

To address these general inquiries, the following research questions were raised:

1. How is the performance of thermally insulated basement envelopes addressed through hygrothermal simulations in the existing literature?
2. How are the hygrothermal simulation procedures (physical models) for basements verified with full-scale measurements?
3. How may the exterior boundary conditions below grade for basement envelopes be determined?

Certain limitations were determined. Literature focusing on crawl spaces, air leakages through the building envelope, heat transfer simulations not accounting for moisture content in the ground, whole building energy simulations or heating and cooling systems, the drying of porous materials (particularly for foods), or the hygrothermal behaviours of masonry walls, wood, or other bio-based materials commonly used above grade or in moisture buffering research, is not addressed.

2. Theoretical framework

The fluid flow, heat transfer, and mass transfer can be described using mathematical descriptions [23]. Typical examples of diffusive equations include Fick's law of diffusion and Fourier's law of heat conduction. Typical examples of diffusion-like transport equations are Darcy's law for water flow and Darcy's law for air flow in porous systems [24]. This knowledge is combined with the laws for the conservation of momentum, mass, and energy [23]. This combination of equations results in a set of partial differential equations (PDEs) for describing the laws of physics for the space and time-dependent descriptions [24]. When laws from several different physical descriptions are combined to describe systems where several phenomena interact, they are called multiphysics systems [25]. The mathematical model of such a system can consist of one or several PDEs (describing the relevant laws), together with boundary and initial conditions. Normally, the right-hand side of the PDE represents the transfer of heat and moisture, as quantified by different material properties and different potentials. The left-hand side represents the storage [26]. The solution to the PDEs is represented by dependent variables (e.g. temperature fields, RH fields, or velocity fields) described in space and time along the independent variables x, y, z, and t [25].

Although mathematical models have a limitation in that analytical solutions can only be found in very special cases (such as in certain combinations of equations and simple geometries), modern numerical methods for solving PDEs can handle nonlinear problems as well as complicated geometries, by providing an approximation of the solution to a well-posed mathematical model. Put another way, discretisation of a mathematical model results in a numerical model for the described system [25]. The numerical methods commonly used for this discretisation are the finite element method, finite difference method, finite volume method, and boundary element method [27]. A numerical model is a discrete approximation of a mathematical model, and the difference between the solutions to the numerical and mathematical models is called the truncation error. The error approaches zero when the element size (determined by the mesh refinement) approaches zero, if the model is stable and consistent [25]. To obtain the solution to the PDEs (within a reasonable amount of time and computational costs) can be challenging, depending on the type of equations, number of independent variables, boundary, initial conditions, and other factors [25]. In particular, detailed 2D or 3D hygrothermal simulations of building components (e.g. a basement envelope part) over long-term periods are considered computationally expensive by consultants in the field of building science.

The commercially available tools WUFI® Pro and 2D (applying the PDEs described in Künzel [28]) is widely used by Nordic consultants and researchers to investigate the heat and moisture performance of building components. New heat and moisture models have also been developed in the last few years (e.g. Refs. [29–31]), that can be applied for complex geometries (up to 3D) using powerful commercial solvers such as COMSOL Multiphysics, Fluent®, or ANSYS-CFD. The drawback of advanced models, however, is that they require much knowledge/resources from the user to implement them in the solver. Another drawback of adopting these advanced solvers is that climate data, boundary conditions and material properties tailored to building physics (available through dedicated software like WUFI® or DELPHIN), are not predefined and need to be implemented in the solver.

Regardless of the physical/solver/tool chosen for a simulation, determining the exterior boundary conditions below grade (as illustrated in Figure 1) constitutes an even bigger challenge, since no recognised methods/procedures seem to exist for this purpose. Great uncertainty is also associated with the ground's variable composition and moisture content, among other factors. These uncertainties suggest that the boundary conditions for thermally insulated basement envelopes should be addressed through a best case/worst case approach, to account for the varying hygrothermal loads inflicted during summer and winter, and upper and lower parts of the basement envelope, in various climates. Addressing the conditions below grade also requires knowledge concerning the physical descriptions of heat and moisture transfer in soil and soil boundary conditions, which may differ from those normally used for building components.

3. Methodology

First, a scoping literature study was performed, targeting scientific research concerning hygrothermal simulations or measurements of thermally insulated basement envelopes. Second, ten comprehensive studies were subjected to scrutiny, and valuable experiences from their methodologies and results were identified. After completing the evaluation of the ten studies focusing on basement envelopes, an additional search was conducted, focusing on hygrothermal simulations of slabs-on-grade. Citation chaining was further used to identify comprehensive studies not caught by the initial searches. Two additional studies were selected and included in the results.

The method used in this scoping study is based on the framework described by Arksey and O'Malley [32] and involves a six-step procedure: 1) identifying the research question, 2) identifying relevant studies, 3) selecting studies, 4) charting data, 5) collating, summarising, and reporting the results, and 6) consultation. According to Arksey and O'Malley [32], multiple databases should be included in the search. In this study, Science Direct was selected as the main search engine for scientific papers and journal articles. Google Scholar was selected for complementary and broader searches (including results from additional scientific journals, scientific publications, and grey papers). The search terms (combinations of keywords) were carefully selected based on the main author's qualitative judgment and on experience from previous work. The search terms, search engines, and limitations are shown in

Appendix A for the initial search and Appendix B for the complementary search.

The initial search identified 22 studies relevant for the scope of this review. Several of these concerned the same research, the same method, or were conducted by the same authors. A thorough description of the selection process that determined the ten particularly interesting studies for further review is also included in Appendix A. The additional search identified two studies. The selected studies addressed hygrothermal simulations from somewhat different perspectives. To identify valuable experiences from these perspectives, each study was subjected to scrutiny. A challenge in this context is that these studies are typically more concerned with the outcome of the simulations, rather than the simulation methodology itself. As such, in some cases, the description of the methodology was deficient.

4. Results

4.1. General overview of the material

Ten particularly interesting studies focusing on basement envelopes were selected for detailed review. Because the ten studies vary in terms of scope and objectives, they are examined in detail to enable a thorough comparison of their approach. Four studies investigated the hygrothermal performance of basement walls, three studies investigated the heat and moisture transfer in the soil domain, and three studies mainly focused on the thermal performances of basements but considered the varying moisture content in the soil. Two studies focusing on slabs-on-grade were also selected for detailed review.

Table 1 summarizes the selected studies and their main methodologies. Detailed descriptions of the boundary conditions of the studies are too substantial to include in a simple manner in Table 1. Instead, this is described in the following chapters (4.2–4.5), along with the studies' purposes, methods, results, and physical measurements. It is chosen to recount the methodology of the studies with a high level of detail, so that the implications of the individual choices in their simulation methodology can be adequately understood.

4.2. Hygrothermal performance of basement walls

Only two of the four studies focusing on the hygrothermal performances of basement envelopes performed both hygrothermal measurements and hygrothermal simulations and compared the results (Goldberg & Harmon [33], Straube [34]). Both mainly concerned the hygrothermal performances of interior insulation systems for walls.

A comprehensive study was reported by Goldberg and Harmon [33], concerning the hygrothermal performance of retrofitted thermally insulated hollow masonry block foundations. Both hygrothermal measurements and simulations were performed. The objectives were to test different retrofit systems, and to develop long-term hygrothermal performance data for foundation walls in cold climates. The experimental work was conducted in Minnesota (2.5 year period). The test setup included five 'bays' with identical walls in the north and south directions. The walls had either interior insulation or exterior insulation on the upper half of the wall. Different backfill types and waterproofing membranes were investigated. The indoor temperatures were set to 20 °C in the heating season and 15.6 °C in the cooling season (no air conditioning). The climate data, below grade soil moisture content, and temperature profiles were thoroughly collected. The experimental data was used to investigate the validity of the hygrothermal simulation program 'WUFI®2D' and the 'Building Foundation Energy Transport Simulation' (BUFETS) program (3D). The authors found that WUFI®2D might not be capable of modelling soils directly, as it failed to yield a solution to the moisture transport equation. According to Goldberg and Harmon [33], WUFI®2D uses a single transport equation with RH as the transport variable for both water vapor and liquid water diffusion fluxes. Although this method is satisfactory for most building materials, it becomes problematic in the soil regions above the groundwater table, where the soil RH generally exceeds 99%, and where the dew point depression is less than 0.2 °C. It was not possible to resolve the problem with program developers but deactivating the bulk water capillary hydraulic conduction transport was a partially successful solution. Approximately 3 months of data were obtained before the simulation failed. A comparison of the measured and simulated heat flux data from BUFETS demonstrated that the experimental data were effective for evaluating the accuracy of thermal simulation programs. The agreements between the measured and simulated wall and soil temperatures were better in the heating season than in the cooling season, and the wall temperature discrepancies decreased with the height above the slab. The likely causes for the discrepancies (as recognised by the authors) were the BUFETSs inability to model buoyant cavity flow loops in hollow masonry block walls, and their inability to model a water table with a seasonally varying height and temperature. The absence of a soil moisture transport model (enabling the calculation of seasonally varying thermal conductivities as a function of soil moisture content) was also recognised as a possible cause. The simulated masonry block core RH profiles for the 3 months simulated by WUFI®2D were compared to those measured; however, a very substantial difference between the simulation and measurements was shown.

Another study comparing hygrothermal measurements and simulations was conducted by Straube [34]. Both field monitoring and 1D hygrothermal simulations were performed. The aim was to increase the understanding of the hygrothermal performances of concrete basement walls with different interior insulation systems. Four concrete test walls with different insulation and varying vapor control layers were monitored for 1 year. Spray-applied damp-proofing and a dimpled drainage mat were applied on the exterior side. The newly built basement was unfinished but heated (approximately 20 °C), and the construction moisture load remained significant. The wood moisture content, temperature, and RH sensors were located in groups at three different heights: near grade, in the middle, and at lower locations below grade. The soil temperature and moisture content were measured at three depths at two lateral locations. The temperature and RH were also measured indoors and outdoors. Hygrothermal 1D simulations were performed using WUFI®Pro for the near grade, middle, and lower locations of the four walls. The validation of the temperatures at the near-grade location (insulation–concrete interface) showed a lack of correspondence. Much lower temperatures were predicted as compared to the measurements, especially during winter. The deviations were far too large to be explained by wetness or compacted insulation, or a dryer concrete than that simulated. The measured soil temperatures were used to further investigate the deviations. It was likely that the heat flow to/from the soil affected the upper parts of the walls. Straube [34] concluded that the lack of temperature correlation in the above-grade simulation prevented full validation, and that a 1D simulation simplification was unfavourable. The below grade simulated temperatures had a better agreement with the measurements, probably owing to the lack of solar influence and slow temperature variations over time. The simulations and measurements of the RH in the middle of the insulation–concrete interface were compared. The RH levels were quite different, especially for low-permeance systems. Possible reasons for this deviation included air leakage, vapor diffusion, 'flanking,' or dryer concrete in the measurements than indicated by the simulations. All the RH values were high, however, and a cause for concern. Two other studies (Fedorik et al. [35] and Pallin [36]) investigated the hygrothermal performances of retrofitted basement walls using only hygrothermal simulations. Fedorik et al. [35] investigated the impacts of multiple refurbishment strategies for concrete basement wall designs from different decades. The main objective was to compare the thermal insulation performance, structural drying, and mould growth risk. The hygrothermal simulations were performed using 'DELPHIN' 5.8 and run for 5 years (the first 4 years were to achieve hygrothermal stability). The underground structure and soil, where the humidity was mainly 100%

Table 1
The studies selected for detailed review.

		Main focus	Simulations				Validation/ verification	Measurements					
			Hygrothermal	Only thermal	Component included	Exterior boundary condition below grade		T	RH	Moisture content	Precipitation	Other	Duration
Hygrothermal performance of basement walls, see Chapter 4.2	Goldberg & Harmon [33] USA (2015)	Hygrothermal performance of hollow masonry block foundation retrofit	WUFI®2D	BUFETS6 (2D)	Wall, floor and ground	From measurements	Yes	Interior, exterior, in wall, soil	Interior, exterior, in wall,	Soil, masonry block, wood	yes	Snow depth, solar radiation, wind, barometric pressure	1.5 years
	Straube [34] USA (2009)	Hygrothermal performance concrete walls with interior insulation systems	WUFI®Pro 4.0 (1D, 3 heights)		Walls	From measurements	Yes	Interior, exterior, in wall	Interior, exterior, in wall	Soil, wood	no		1 year
	Fedorik et al. [35] Finland (2019)	Hygrothermal performance of refurbishment strategies for old concrete basement walls	DELPHIN 5.8 2D and/or 1D?		Walls and ground separately	From fully coupled simulation of ground	No	Not addressed					
	Pallin [36] Sweden (2013)	Risk assessment of hygrothermal performance of a concrete wall retrofitted with exterior vapor permeable EPS	WUFI2D (+ Pro?)	WUFI®2D	Walls and ground	From thermal simulation of ground	No	Not addressed					
Heat and moisture transfer in the ground adjacent to basements, see Chapter 4.3	Pallin & Kehrer [37] Sweden & USA (2013)	Soil properties applicable for simulation and thermal behaviour of 20-m-deep soil column	WUFI®Pro		Ground		Yes	In air, soil		n.a.	?	?	4 years
	Janssen et al. [38] Belgium (2004)	Influence of soil moisture transfer on heat loss via the ground for insulated basements (wall + floor)	Program not specified. 2D+1D	Program not specified.1D	Ground		No	Not addressed					
	Deru [39] USA (2003)	Ground-coupled heat and moisture transfer from buildings. Insulated concrete basement (wall and floor)	GAHMT (2D)	GHT2D (2D)	Ground		Yes	In air, in soil					20 days
Thermal performance of basements, see Chapter 4.4	Saaly et al. [40] Canada (2020)	Annual energy loss from a concrete basement (walls +floor). Including freezing of soil and change in thermal properties.		COMSOL (3D+2D)	Walls + ground	n.a.	No			Soil (frozen /not frozen)			No

(continued on next page)

Table 1 (*continued*)

		Main focus	Simulations					Validation/ verification	Measurements					
			Hygrothermal	Only thermal	Component included	Exterior boundary condition below grade			T	RH	Moisture content	Precipitation	Other	Duration
	Swinton et al. [41] Canada (2006)	Thermal performance of insulated concrete basement walls	Not addressed						Interior, exterior, in wall, soil		Soil	√		
	Zoras [42] Greece (2009)	Building Earth-Contact Heat Transfer.	Refers to the work of others						Not addressed					
Hygrothermal performance of slabs-on-grade, see Chapter 4.5	Rantala & Leivo [43] Finland (2009)	Heat, air, and moisture control in slab-on-ground structures	Only steady-state 1D		Slab	100 % RH		No	Fill layer below slab		Fill layer below slab		Micro-biological conditions	Long-/ short term
	Dos Santos & Mendes [44] Brazil (2006)	Heat and moisture transfer in soils combined with building simulation	Program not specified 3D		Ground, slab and building			No	Not addressed					

RH, were considered as problematic areas in the simulations. The computation slowed considerably when the moisture content achieved full saturation. The complex computational models required long computational time, and often lead to unstable convergence. The numerical models, geometries, meshes and the ground size included in the models was not fully described. The precipitation and capillary transport in the soil were, according to the article, taken into account, but the initial conditions, moisture content, and material properties of the soil were not described. Other material properties, including those of gravel, were stated. Direct rain leakage and air convection values were omitted. A Finnish guideline (RIL 107–2012) and Jokioinen 2004 test year were employed for the interior and exterior conditions, respectively. The ground surface boundary conditions were not described. The snow cover, freezing or thawing of soil, solar shading, and net movement of ground water below the building were omitted. As the thermal resistance of a basement structure directly affects the ground temperature distribution, each numerical model (each refurbishment strategy) was simulated in two phases. First, the temperature distribution throughout the entire geometry was simulated. Second, the ground area was excluded, and thermal boundary conditions were represented by the results from the first simulation (walls split into 9–10 sections with 400 mm height). The results confirmed previous research showing that exterior thermal insulation is the most robust solution for basement walls. The results also showed that if only interior insulation is applicable, using capillary-active materials is efficient for enabling inward drying (if a limited thickness is applied). The study concluded that refurbishment of basement walls should be analysed in detail. Pallin [36] described a hygrothermal risk assessment procedure. To show the procedure in practice, hygrothermal simulations were performed for a concrete basement wall. The main objective was to investigate the effect (s) of the outward drying, and how it was affected by different types of soil and indoor climates. The basement wall represents the target of a common retrofit approach, where permeable drainage and insulation boards are positioned on the exterior surface below grade and covered with landscape fabric. The previously removed ground material is used as backfill. In Pallin's study, hygrothermal simulations of a wall were performed in WUFI®2D for 12 different classified soil textures. One consecutive year was assumed to be sufficient for the comparison analyses. The concrete and soil were assumed to be water vapor saturated (100% RH). The climate of Gothenburg (Sweden) and a south-west direction were used, as solar radiation, increases the soil temperatures and reduces the drying potential. The basement was set to a constant temperature of 18 °C. The heat and moisture fluxes were studied at three depths from the ground surface. Temperature variations at the same depths were studied for both sides of the drainage/insulation board. The results showed that the soil temperatures varied significantly on a yearly basis, depending on the distance to the ground surface. The temperature variations at the studied depths were applied to determine the variations in the water vapor contents at the wall surface and in the soil. When the temperature of the soil was higher than the surface temperature of the wall, the moisture flux was turned inward. The deviations between the different soil textures were small. The variations in the heat flux between the 12 soil textures were higher, and deviated by approximately 10% depending on the soil type. The largest heat flux deviation was observed between silty clay and sand. The simulations showed that only small amounts of precipitation can penetrate the insulation/drainage board if the drying potential is positive. If more water penetrates, the drying potential will be equalised or reversed.

4.3. Heat and moisture transfer in the soil adjacent to basements

Three studies were found concerning heat and moisture transfer in the soil domain. Two of them performed numerical simulations and investigated the influences of precipitation and different types of soil on the heat loss from buildings. The third study investigated the implementation of precipitation in hygrothermal simulations of basements.

Janssen et al. [38] performed hygrothermal simulations of an insulated basement and the surrounding soil to investigate the influence of soil moisture transfer on building heat loss via the ground. A parameter study was conducted with varying climates, precipitation, soil types, thermal resistances of basement walls and floor, basement widths, and shapes of the foundation (ground floor). Completely coupled simulations (coupled equations for soil heat and moisture transfer and the full formulations of the surface heat and moisture balances) were compared with linear thermal simulations (moisture contents kept at their respective yearly averages from the coupled simulation, i.e. no moisture transfer was included; only thermal conduction). The fully coupled simulations were initialised with the matric head field and temperatures from a steady-state initial simulation and run at intervals of 10–15 years. Loam was used as a typical soil, and a bare soil surface was assumed. Climate data were obtained from the designed reference years of Essen (Germany). A water table was assumed to be present at the bottom of the soil domain, and thus saturation was imposed as a hygric boundary condition. Owing to the low velocities of the ground water flow, an adiabatic thermal boundary condition was applied. As both radiation and evaporation contribute to the surface heat balance, the external surface temperature, and not the air temperature, was used in the definitions of the thermal permeances. A finite element spatial discretisation and fully implicit time-stepping scheme were used to solve the transfer equations and boundary conditions. The Newton–Raphson algorithm was employed to improve the convergence of the iterative procedure (because the boundary conditions were highly nonlinear). A 'variable time step' algorithm was also used. The daily average climate was used, and did not notably affect the transfers of heat and moisture in the soil as compared to hourly data. The linear simulations were also compared to linear calculations using current European standard for heat loss via the ground [21]. The comparison of the fully coupled and linear heat losses showed that the coupled simulation (moisture transfer in the soil included) yielded higher heat losses. Janssen et al. [38] showed that the increase in heat loss could mainly be attributed to (1) the greater amplitude of the soil surface temperature's amplitude, (2) the variation of the thermal conductivity with moisture content and (3), the advection of sensible heat by liquid moisture transfer. The parameter study showed that neither basement width nor soil type significantly affected the influence of the coupling. However, it was observed that, despite the soil type differences in regard to hygrothermal properties, the transfers of heat and moisture in the different soils were similar. Ultimately, the hygrothermal behaviour of the soils was governed by the climate. This deduction was also confirmed from the significant effects of climate and precipitation on the difference in the linear/coupled heat loss. Janssen et al. [38] concluded that the increased heat loss difference between coupled and linear simulations cannot be regarded as insignificant, and that soil moisture transfer has an indisputable influence on building heat loss via the ground. Janssen et al. [38] also showed, by comparing the two linear simulations, that using the conservative values provided by the European standard [21] introduces far greater deviations than those owing to coupling phenomena, and that an accurate assessment of the thermal conductivity of the soil is therefore not feasible.

Deru [39] performed 2D simulations of a basement and the surrounding ground, with and without a rain event. The objective was to investigate the moisture transfer in the ground and its impact on building heat loss. Deru [39] developed programs called 'GHAMT' (for 2D heat and moisture transfer) and 'GHT2D' (for 2D heat conduction). The basement was simulated for summer and winter conditions, with and without insulation, and with different types of soil. Vegetation was assumed on the ground surface boundary. The boundary at the bottom was 10 °C, and saturated. Along the sides of the model, the heat and moisture fluxes were set as zero. The groundwater was modelled as a saturated boundary. To determine the initial temperature and moisture fields for the simulations, detailed pre-simulations were performed with varying weather conditions. Deru [39] showed that when rain was added during the summer conditions, the heat loss showed a jump, and then converged towards the dry case as the soil dried out. For the cases with winter conditions, very little change was shown when rain was added to the surface. The contour plots of the soil volumetric moisture content in the ground for the uninsulated basement summer cases showed that the moisture distribution in the soil was affected very little by the presence of the basement, for all of the simulated summer cases. According to Deru [39] this demonstrated that it might be possible to approximate the change in the soil moisture content with depth around a building by using a 1D column of soil (which is much easier to simulate). Hence, a heat transfer program could be used, which is much faster (including only the variation in thermal conductivity with depth). A simple freezing model was used in the simulations; however, according to Deru [39] the soil thermal conductivity and moisture behaviour could be significantly affected by freezing. If cyclic freezing and thawing occurred, the various types of ice formation and complex soil moisture behaviours at the freezing front would require a more detailed model. A comparison of GHAMT and GHT2D showed that GHT2D should consider the variation of the soil thermal conductivity with depth, and accurately model the ground-surface boundary condition (including the effects of evapotranspiration). Deru [39] suggested a simple method for modelling the variation in the soil, with at least two values for the soil thermal conductivity with depth, to account for the higher soil moisture content below the top of the soil. According to Deru [39], the evapotranspiration at the ground surface could have a large impact on the calculated heat transfer from the basement walls, and the results should be bracketed between the potential value and zero (unless there is knowledge of the exact level of evapotranspiration). According to Deru [39] a soil thermal conductivity value is usually chosen with very little knowledge of the soil type and moisture content, despite its large impact on the hygrothermal properties of the soil (e.g., the thermal conductivity can change by a factor of ten with the moisture content).

Pallin and Kehrer [37] defined properties for 12 classified types of soil and aimed at evaluating the heat and moisture performance of different basement assembly types in several climate zones. However, they found that the applied assumptions typically used in hygrothermal tools for the implementation of precipitation are inadequate. The precipitation typically functions as a boundary condition; thus, the moisture load initially only affects the grid element closest to the border. If the element is saturated, the moisture buffering capacity (and hence, the surplus of moisture) is neglected. Although this assumption might be applicable for a vertical wall with drainage, it is not applicable at the soil surface, where most of the precipitation will be absorbed eventually. Pallin and Kehrer [37] investigated how the amount of precipitation neglected during the simulations could be decreased. A 20-m deep 1D soil column was simulated in WUFI®Pro and compared to soil temperatures measured hourly at two depths. The precipitation in this model was distributed directly into the first four elements as an impregnated source. A rather good agreement was shown when comparing the simulated and measured temperatures at a depth of 1 m. According to Pallin and Kehrer [37] the simulations required the following improvements: (1) better account for the liquid uptake of precipitation on the soil surface, (2) address the moisture transfer at the lower boundary (the infinite ground), (3) provide a better heat-transfer coefficient at the soil surface (which varies with a number of factors), and (4) address snow cover (and its effect on the surface thermal resistance and long- and short-wave radiation).

4.4. Thermal performance of basements

Three studies mainly focused on the heat loss from basements. The first study investigated how including freeze-thaw cycles in the soil affected the heat loss. The second investigated the in situ thermal performance of basement walls and effects from weather extremes. The third reviewed different methods for predicting heat transfer in the ground adjacent to buildings.

Saaly et al. [40] performed thermal simulations (2D + 3D) to investigate the effects of freeze-thaw cycles (pore water phase changes) on the heat transfer of a concrete basement in a severely cold climate (frost depth of approximately 2.5 m). Both frozen and unfrozen soil samples, from several depths and locations on site, were analysed to determine the variability and soil thermal properties. Different thermal insulation scenarios and the use of draining backfilling materials were investigated. COMSOL Multiphysics was used; the simulation models included a large part of the adjacent soil and the simulations were run for one year. Constant average soil thermal properties was compared to variable thermal properties (soil assumed to be homogeneous, isotropic, and incompressible). The initial temperatures were all uniform. The thermal properties of the concrete and insulation were considered as constant. The soil thermal properties varied as the temperature dropped below the freezing temperature; hence, the thermal soil properties depended on the latent heat of fusion and the fractions of water and ice in the soil pores. To include this numerically, the soil was assumed to be fully saturated. The frost heave was assumed to be negligible, and only heat transfer by conduction was included in the soil. The uninsulated basement showed an approximately 34% higher energy loss when phase change in the soil was included. Without including freezing, the overall energy efficiency of the basement increased by approximately 51% as insulation were applied. This enhancement increased to 60% once freezing in the soil was included. The results also showed an approximately 22% higher heat flux as predicted by the 2D model relative to that predicted by the 3D model. The layer of backfill materials surrounding the basement walls decreased the basement heat loss by 16.5%.

Swinton et al. [41] investigated the in situ thermal performance of two concrete basement walls, insulated with exterior spray polyurethane foam (SPF) over the full height and exposed to the climate of Ottawa (Canada) for 2.5 years. Specimens with horizontal z-bars (soil sloped towards the wall) were compared to specimens with z-bars fastened vertically (soil sloped away from the wall). Both specimens were in direct contact with the soil below grade. The boundary conditions were recorded, including observations of weather extremes. Measurements were performed in the soil and on the surface. The soil temperatures and moisture content were recorded, and four separate soil analyses were performed to characterise the soil environment; however, the results were not further described in the study. The differences in the observed thermal performances of the specimens were qualified with information from monitoring. The results showed that the thermal performance was relatively steady, with an equal or improved performance during the second heating season. The thermal performance did not appear to be significantly affected by major rain and thaw periods. The system with horizontal z-bars yielded consistently superior thermal performance compared to the system with vertical z-bars. The results also showed that periodic temperature deflection 'spikes' occur, corresponding to periods with heavy precipitation or winter thaw events. In summer, the temperature profile at the insulation/soil interface deflected upwards, owing to warm rainwater moving down. In winter, the deflections were downward, because the melt water temperature was initially 0 °C, and thus cooled the soil and insulation at the interface.

Zoras [42] reviewed methods for predicting heat transfer in earth-coupled structures and divided them into four categories: analytical/semi-analytical methods, numerical methods, manual methods, and design guides. According to Zoras [42], analytical methods provide far more accurate results; however, solutions are restricted to linear heat conduction (e.g. dry soil) and simple geometries. Manual methods and design guides, in contrast, suffer from simplicity and empirical inefficiencies. Numerical simulations can be performed using robust coupled tools, however, the lack of initial conditions for the underground domain causes inefficiencies, owing to the inevitable multi-year simulations needed to approximate realistic soil temperature fields. Zoras [42] briefly addressed an idea for future work. It involved being able combine an unconditionally stable implicit scheme, generally fast explicit scheme, and flexible variable time-stepping scheme. This combination could be implemented for all finite volume-based numerical models. For most of the above-mentioned methods to be implemented, the unique entities defined therein must be described by linear equations. In particular, the variation in conductivity owing to temperature changes is a very important issue, as it is a non-linear phenomenon. During numerical simulations, this can only be handled with iterative processes (extremely time consuming, especially for simulations over long periods). According to Zoras [42], it is possible, through the application of Kirchhoff's transform, to remove the non-linearity of the variable conductivity owing to temperature fluctuations, i.e. to convert the non-linear effects into linear effects. The actual solution had previously been integrated into a finite element formulation for non-linear heat conduction. Combined with superposition methods, this particular transformation could be advantageous, e.g. it could lead to fast simulations where non-linear phenomena would be considered. The study concludes that a future fully complete tool must consider the variable conductivity, heat and moisture coupling, changes of phase, snow cover, convection, and evaporation at the earth's surface. The study refers specifically to the very comprehensive review concerning the handling of soil water content by Rees et al. [45], and Krarti's method [46] for addressing convection and evaporation at the earth's surface.

4.5. Hygrothermal performance of slabs-on-grade

Two studies concerned the hygrothermal performance or simulation of slabs-on-grade. The first investigated the relative humidity in the drainage layers below slabs and the second integrated a coupled three-dimensional heat and moisture transfer model of the ground beneath a slab to a single-zone building model.

Rantala & Leivo [43] measured the moisture content, the thermal conditions and the microbiological conditions in the coarse-grained fill or drainage layers beneath slabs. Long-term field tests were performed on new buildings and a series of short-term in situ surveys were performed on already established buildings. The water content of fill layers (samples from 33 different buildings) was determined at the fill/slab interface using the weighing–drying–weighing method. Different types of slabs, both with and without insulation, were included. 49 soil samples, taken beneath the ground slabs, were cultured in the laboratory so the microbe content could be studied. The objective of the study was to increase the knowledge of the boundary conditions at the slab-fill interface and to determine the conditions during the lifespan of seasonally heated buildings. Results showed that the measured water contents were, in almost every single case, higher than the hygroscopic equilibrium moisture content of the material in high RH (RH $\approx$ 100% $\leftrightarrow$ w$<$0.5% by weight). The samples were considered to be at the annual minimum because they were taken in late winter/early spring (while there is still heavy frost on ground surface and the groundwater table is at its lowest). Temperature measurements showed that, despite the significant variation in the outdoor air temperature, the temperature in fill layers at the central part of the slabs was relatively warm throughout the year. Fungal or bacterial growth was detected in 98% of the test specimens. Bacteria were detected in all age groups of the buildings and in the oldest structures. Some of the concentrations were extremely high. According to Rantala & Leivo [43], the high microbe concentration in the fill layer is a normal boundary condition related to the existing thermal and moisture conditions of the layers, and is not a sign of moisture damage. Rantala & Leivo [43] also investigated the hygrothermal performance of slab-on-ground structures theoretically under steady-state conditions. Two different floor structures of in situ cast concrete were investigated with varying combinations of thermal and moisture parameters of the structural materials and changing surrounding conditions. Humidity values at the slab/floor-covering interface was compared as the RH of the lower surface of the floor covering is usually critical for the behaviour of the structure. Results showed that the importance of the water vapor resistance properties of the floor covering material was significant to the overall hygrothermal performance of the structure and that the thermal insulation should be placed mainly or entirely underneath the slab.

Dos Santos & Mendes [44] present a coupled three-dimensional heat and moisture transfer model of the ground beneath a slab which is integrated to a single-zone building model. One objective of the study was to investigate how important moisture in soil can be in different scenarios, taking a coupled three-dimensional effect in to account. A concrete floor was considered, but no moisture barrier or insulation were included in the floor. Solar radiation and rain were considered. The exterior climate was represented by sinusoidal functions from Curitiba in Brazil and the annual average temperature was set to 20 °C. The governing equations used for the heat and moisture transfer in the soil was based on the theory of Philip and De Vries. Sandy silt soil and sand with properties strongly affected by temperature and moisture content were used in the study. According to Dos Santos & Mendes [44], the simulation time step, the grid refinement, the pre-simulation time period, the size of the physical domain, the boundary conditions, the convergence errors and the required computer run time, have to be chosen carefully in order to accurately predict temperature and moisture content profiles in soils under different weather data. A sensitivity analysis showed that the grid size had to be refined at the upper surface which is in contact with the air. It also showed that the results were less sensitive to the time step due to the robust algorithm used and due to the linearization of vapor concentration difference at soil top surface.

5. Discussion

This article has examined three research questions, the answers to which will be discussed in the following sections:

5.1. *Hygrothermal simulations of thermally insulated basement envelopes in existing literature*

Only four individual studies identified in this review —Goldberg and Harmon [33], Straube [34], Fedorik et al. [35] and Pallin [36]—actually addressed hygrothermal simulations of basement envelopes. Different approaches were used by these authors to define the boundary conditions below grade. Pallin [36] simplified the soil domain by assuming fully saturated soil, and used a corresponding constant thermal conductivity for the entire ground. The walls and soil were simulated first to determine the annual temperature variations on the exterior sides of the walls; this information was used to investigate the hygrothermal performance of the walls. This was the same two-step approach used in Ref. [22]. Using an average 'conservative' thermal conductivity for soil are also proposed in the current European standard for modelling heat loss from buildings through the ground [21]. Although this simplification might be sufficient to appropriately estimate heat loss, it might not be sufficient for investigations of hygrothermal performance. Fedorik et al. [35] used the same two-step approach, but additionally included the effects of rain and capillary transport in the soil. According to Fedorik et al. [35] they illustrated that hygrothermal simulations of fully saturated underground structures and soil can be performed using the commercially available program DELPHIN 5.8, however, the complex computational models required long computational time, and often lead to unstable convergence. The study also lacked a thorough description of the numerical method(s) and inputs used. Straube [34] performed 1D hygrothermal simulations of basement walls at three different height locations, using measured temperature variations and assuming 100% RH for the wall's exterior boundary conditions below grade. However, the simulations were not successful for parts of the walls near the ground surface. Goldberg and Harmon [33] attempted to perform 2D hygrothermal simulations for basement walls and the surrounding soil. They divided the soil into three domains with different thermal properties to account for the different soil types and measured moisture contents. Unfortunately, they found that WUFI®2D failed to yield a solution to the moisture transport equation.

The remaining studies mainly focused on the thermal performances of basements; nevertheless, the methods used are highly relevant, because they address the soil moisture content and/or moisture transfer. Deru [39] and Janssen et al. [38] investigated the impact from soil moisture transfer on the heat loss from basements. According to Deru [39], the thermal conductivity of the soil can change by a factor of ten with the moisture content, and is the most important parameter in determining the ground-coupled heat transfer. Deru [39] proposed that a 1D column of soil (which is much easier to simulate) might be used to approximate/pre-simulate the changes in the soil moisture content, and thus the thermal conductivity with depth around a building. Janssen et al. [38] further investigated the differences between completely coupled heat and moisture simulations with linear thermal simulations and found that soil moisture transfer has an indisputable influence on heat loss. Janssen et al. [38] showed that, despite the soil type differences in regards to hygrothermal properties, the transfers of heat and moisture in the different soils were similar and ultimately governed by the different climates. The foundation width was shown to be of lesser importance. Due to the inaccuracy of determining actual soil properties, however, Janssen et al. [38] concluded that using the conservative values provided by the European standard [21] introduces far greater deviations than those introduced owing to coupling phenomena. The basement in the study of Janssen et al. [38] had a thermal transmittance of 0,7 W/m^2. Janssen [47] investigated the difference between coupled and linear simulations for basements with different thermal transmittances (0.35, 0.7 and 5.4 W/m^2) and showed that the difference increased with less insulation, i.e. the difference in heating season heat losses were 8.9, 10.1 and 13.6% respectively.

The experiences from Goldberg and Harmon [35], Fedorik et al. [35], and Pallin and Kehrer [37], show that WUFI®2D and DELPHIN 5.8 might not be optimal to use for the coupled heat and moisture transfer in the soil. These tools are tailored for porous building materials, assemblies and building envelopes. In WUFI® precipitation (in the form of driving rain) can be included as a boundary condition inflicting a source of moisture for the exterior surface to draw from during rain events and then further redistributed in the component. The liquid transfer by gravity (and transfer of sensible heat) is not included. For both DELPHIN 5.8 and WUFI®, the high moisture contents in the soil and the fine mesh refinement required was challenging numerically, i.e. required long computational time, often leading to unstable convergence or failing to yield a solution to the moisture transport equation. According to Zoras [42], future fully completed tool should address variable conductivity, heat and moisture coupling, changes of phase, snow cover, convection, and evaporation at the earth's surface. Zoras [42] points out that numerical simulations of earth-coupled structures suffers from inefficiencies, owing to the inevitable multi-year simulations needed to approximate realistic soil temperature fields as initial conditions for the soil/ground domain. This is also experienced by Janssen et al. [38], when performing two-dimensional fully coupled simulations of the soil adjacent to a basement, using the equations derived in Milly [48]. They experienced that very small time steps were necessary, at the onset of a rain event, to adequately simulate the absorption and the drainage of the precipitation. The large simulation domains, the rather difficult transfer equations and boundary conditions, and the long simulation intervals needed to reach the steady-periodical solution, made computational efficiency an essential concern. To considerably accelerate the convergence towards a steady-periodical solution, the two-dimensional simulations were initialised with temperature and matric head fields, from a steady-state initialisation run. From there, a 10–15 year of simulation was needed to attain a steady-periodical state. The effect of including freeze-thaw cycles in the soil were not addressed by Janssen [38], but might be important to consider in colder climates. Saaly et al. [38] performed thermal simulations in COMSOL Multiphysics and included freeze–thaw cycles in the soil by using a thermal conductivity which varied as temperature dropped below zero. Although the freezing model used was simplified, the study illustrates how a basement wall and floor and the large part of the adjacent ground, can be simulated, in both two and three dimensions, including a varying thermal conductivity for the soil domain.

5.2. Verification with measurements

Goldberg and Harmon [38] and Straube [34] are the only two studies that have attempted to verify hygrothermal simulations of basement walls using measurements. Pallin and Kehrer [37] and Deru [39] verified the heat and moisture transfer in soil by comparing hygrothermal simulations with measured temperatures only.

In Goldberg and Harmon [38] the agreements between the measured and simulated wall and soil temperatures were better in the heating season than in the cooling season, and the wall temperature discrepancies decreased with the height above the slab. The likely causes for the discrepancies recognised by the authors were the inability of BUFETS to model the buoyant cavity flow loops in the hollow masonry block walls, and its inability to model a water table with a seasonally varying height and temperature. They also recognised the absence of a soil moisture transport model (enabling the calculation of seasonally varying thermal conductivities as a function of soil moisture content) as a possible cause. Perhaps a better correspondence between measurements and simulations could have been achieved if concrete had been used in the experiment instead of the hollow masonry block walls, or if the soil had been simulated separately using the methodology adapted in Janssen [38].

For Straube [34] the simulation at the near-grade location yielded a lack of correspondence with the measurements. It was considered likely that heat flow to/from the soil affects the above-grade part of the wall, and that a 1D simulation simplification is not favourable when considering basement walls. In contrast, 2D hygrothermal simulations of the concrete basement walls, such as those performed by Fedorik et al. [35], might have yielded a better correspondence with the measurements.

Pallin and Kehrer [37] simulated a 1D soil column using WUFI®Pro and compared the results with soil temperatures measured hourly at two depths. The results showed a rather good agreement when comparing the ground temperatures from measurements and those from simulation at a depth of 1 m, but improvements to the simulation model were required.

Deru [39] compared the simulations of a soil column to measured soil temperatures. Unfortunately, moisture data that would have provided a more decisive validation were not measured. The comparison showed the sensitivity of the results at the surface to atmospheric conditions. Short-term variations in the atmospheric conditions were shown to have little effect on the predicted soil temperatures below 0.2 m, but small inaccuracies at the surface were shown to potentially cause the predictions to slowly diverge from the actual behaviour for simulations longer than a few weeks. For simulations without precipitation, the results at all depths slowly diverged from the measured data, owing to the slow drying of the soil. Deru [39] also noted that the presence of persistent snow cover and ground shading could also substantially affect the results.

5.3. Exterior boundary conditions below grade for thermally insulated basement envelopes

This review has provided an overview of the state-of-the-art hygrothermal simulation methods applied to basement envelopes. The following valuable experiences have been identified:

1. 1D simulations of basement walls, at three different wall heights, showed a lack of correspondence with measurements. The near grade location exhibited the largest deviations (Straube [34]).
2. Including the soil moisture transfer in the ground (fully coupled 2D simulations) increases the heat loss (Janssen et al. [38] and Deru [39]).
3. The difference between coupled and linear simulations of heat loss were mainly attributed to (1) the greater amplitude of the soil surface temperature's amplitude, (2) the variation of the thermal conductivity with moisture content and (3), the advection of sensible heat by liquid moisture transfer (Janssen et al. [38]). The difference increases with less insulation (Janssen [47]).
4. The high moisture content in the soil domain is considered problematic using the 2D hygrothermal simulation tool WUFI®2D (Goldberg & Harmon [33]), and often leads to unstable convergence using DELPHIN 5.8 (Fedorik et al. [35]).
5. Using daily average climate data did not notably affect the transfers of heat and moisture in the soil compared to hourly data (Janssen et al. [38]).
6. Hygrothermal boundary conditions for basement envelopes below grade should account for the following:
   - advection of sensible heat by liquid moisture transfer (Janssen et al. [49]), Straube [34];
   - liquid uptake of precipitation on the soil surface (Pallin & Kehrer [38]);
   - moisture transfer at the lower boundary (infinite ground) (Pallin & Kehrer [38]);
   - heat and moisture coupling (Janssen et al. [38] and Deru [39]);
   - convection and evaporation at the earth's surface (Pallin & Kehrer [38]) (Zoras et al. [42]);
   - changes of phase owing to freezing (Zoras et al. [42]) Deru [39] (Saaly et al. [40]);
   - snow cover (Pallin & Kehrer [38]; Zoras et al. [42]).
   - address the inefficiencies associated with the inevitable multi-year simulations needed to approximate realistic initial conditions (soil temperature and moisture fields) (Zoras et al. [42], Dos Santo & Mendes [44]).
7. High RH (RH $\approx$ 100% $\leftrightarrow$ w$<$0.5% by weight) has been measured in drainage layers below slabs (Rantala & Leivo [43])
8. Solar radiation should not be neglected when considering the drying-out capacity of the basement walls, as solar radiation can cause inwards moisture transfer (Pallin [36]).
9. COMSOL Multiphysics can be used for three dimensional simulations of heat transfer from a basement including a variable thermal conductivity for the soil (Saaly et al. [40]).
10. The hygrothermal properties for 12 different soil textures were defined (Pallin & Kehrer [38]).

Adequately determining the exterior boundary conditions below grade for basement envelopes is challenging because the conditions vary along with the height below grade and depends on several varying factors (e.g. the soils' composition, varying moisture content and hygrothermal properties, the thermal resistance of the envelope, the indoor temperature and exterior climate factors). The boundary conditions may be determined from simulations of the adjacent ground together with the basement envelope (or its thermal resistance). This can be done in several ways: (1) the approach used by Janssen et al. [38] including fully coupled heat and moisture transfer simulations for the soil, (2) using only thermal simulations but accounting for varying moisture content or freezing etc. through a variable thermal conductivity like Sally et al. [40], or (3) using only thermal simulations and simplifying the soil domain by assuming a constant thermal conductivity for the soil like Geving et al. [22].

Using the approach by Janssen et al. [38] requires much knowledge from the user, numerous parameters (sometimes unknown), and is considered time consuming due to the inevitable multi-year simulations needed to approximate realistic initial conditions (soil temperature and moisture fields). Using the approach by Saaly et al. [40] or Geving et al. [22] constitutes a more manageable approach in terms of computational costs. However, Janssen et al. [38] showed that the coupled simulations resulted in an increase in heat loss compared to the linear simulations, and that this difference increased as the thermal resistance of the envelope decreased (with less insulation). Janssen et al. [38] also showed that, despite the soil type differences in regards to hygrothermal properties, the transfers of heat and moisture in the different soils were similar and ultimately governed by the different climates. Specifically, the increase in heat loss could mainly be attributed to (1) the greater amplitude of the soil surface temperature's amplitude, (2) the variation of the thermal conductivity with moisture content, and (3) the advection of sensible heat by liquid moisture transfer. However, based on current literature, it is not possible to determine the importance of the coupled simulation for the hygrothermal performance of thermally insulated basement envelopes and whether this effect should be accounted for in the determination of below grade boundary conditions. Hence, further research should focus the impact of including coupled simulations and other varying influencing factors on the hygrothermal performance of thermally insulated basement envelopes, to investigate how the boundary conditions below grade should be determined. Finally, experiences from this review indicate that DELPHIN or a more advanced multiphysics tools (e.g. COMSOL Multiphysics), might be favoured for future research on boundary conditions below grade. Advanced tools provide powerful solvers to reduce computational costs and more flexibility to implement the required physics (e.g. liquid transfer of precipitation by gravity), but require more knowledge and resources from the user for the implementation.

6. Concluding remarks

In cold climate countries, basements are often used as a habitable part of dwellings, representing a major challenge concerning moisture safety design. Assessing the suitability of a basement envelope design or a refurbishment strategy (e.g. ability to dry out), therefore requires an understanding of the heat and moisture transfer within the structures and how it is affected by the exterior boundary conditions and their seasonal variation, both above and below grade. This literature review illustrates the inadequacy of existing hygrothermal simulation tools to replicate actual hygrothermal conditions in basement envelopes and shows the lack of thorough validation of hygrothermal simulations using full-scale measurements. A range of factors seems to affect the exterior boundary conditions, however, no research seems to have been focusing on the relative impact of these various factors on the hygrothermal performance of thermally insulated basement envelopes.

Predefined climate data (e.g., moisture design reference years) can be chosen for the exterior boundary conditions above grade, in the dedicated commercial hygrothermal tools commonly used by consultants and researchers (e.g., WUFI®2D or DELPHIN 5.8). Such predefined boundary conditions should also be made available for the below grade part of buildings, and applicable for different thermal resistances, height below grade, soil types, and climates. The review shows that there is a need for a recognised method/procedure to determine the exterior hygrothermal boundary conditions below grade for basement envelopes without extensive computational effort. Future work aims at improving the hygrothermal simulations for thermally insulated basements by addressing this general deficiency.

Increased knowledge and improved hygrothermal prediction tools can contribute to further improving the durability and energy efficiency of basement envelopes. Moreover, there are significant potential economical savings related to avoiding or delaying expensive repairs on building parts below grade.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Identification and selection of studies for detailed review

A scoping literature study, focusing hygrothermal simulations or measurements of thermally insulated basement envelopes, was performed between January and February 2020. The large number of results provided by the search engines required the development of a manageable strategy for the selection of relevant studies. The selection process was conducted in three steps, as shown in Table A.1. First, a large number of results were sorted by relevance in the search engines. Second, the displayed results were reviewed, and articles were judged by the title alone. Articles clearly not concerning basements were excluded, and articles that might concern basements were selected. In most of the searches, the selected articles were found within the first 30–50 displayed results. Based on a judgment made by the author, reviewing the first 100 displayed results was sufficient, if the last 30 results were not relevant. In one of the searches, articles were still relevant for selection after the first 100 displayed results. In this case, reading through the first 200 displayed results was considered sufficient. Third, the selected articles were more thoroughly examined, and studies not concerning basements were excluded. In total, 85 studies were identified from a review of the titles and 39 of them were relevant to the hygrothermal performances of basement envelopes. Of these, 22 studies of particular interest were selected according to the following criteria: (1) they concerned hygrothermal simulations of walls and/or floors in basements and/or the adjacent ground/soil, or (2) they included measurements of temperatures, RH, or moisture content in basement walls and/or floors and/or adjacent ground that could be used for validation purposes.

Table A.1
Identification of relevant studies and selection of studies for detailed review.

Search engine/ date of search	Search terms:	Limitations in Search engine	Selecting relevant studies (3 steps)			Particularly interesting	Selected for review
			Results (sorted by relevance)	From review of the title	Actually concerning basements		
Science Direct	building AND moisture AND hygrothermal AND simulation AND (basement OR foundation	Limited to research and review articles	183	13	5	Includes hygrothermal simulations or	Of the 22 identified studies, several were related to the same research or written by

(continued on next page)

Table A.1 (*continued*)

Search engine/ date of search	Search terms:	Limitations in Search engine	Selecting relevant studies (3 steps)			Particularly interesting	Selected for review
			Results (sorted by relevance)	From review of the title	Actually concerning basements		
(January 2020)	OR below grade) Should have been: 'below grade' (138)					measurements of basements.	the same author, se Table B.2.
Google scholar (January 2020)	building AND moisture AND hygrothermal AND simulation AND (basement OR foundation OR 'below grade')	Patents and quotes not included	3150	1 (to wide)	1	From Science Direct: 5 (+2 unavailable) From Google Scholar: 15 (+6 unavailable)	Only the 10 newest and most comprehensive were selected for a detailed review and referred to under results.
	hygrothermal AND simulation AND (basement OR below grade)	Patents and quotes not included	1890	1 (to wide)	1		
	building AND hygrothermal AND simulation AND basement	Patents and quotes not included	841	24 (review of the first 100 results.)	15 relevant (+3 already referred to in previous search)		
Science Direct (February 2020)	building AND moisture AND measurement AND basement	Limited to research and review articles	1293	9 (review of the first 100 results.)	5 (+4 already referred to in previous search)		
Google scholar (February 2020)	building AND moisture AND measurement AND basement	Patents and quotes not included	32 700	37 (review of the first 200 results.)	12 relevant (+8 already referred to, 6 unavailable, 9 less relevant, 2 not relevant)		
Total:			40 057	85	**39**	**22**	**10**

Majority of the 22 studies were from the USA (9) and Canada (7) (see Figure A.1). The study publication dates ranged from 1999 to 2020. The main purposes of the studies varied, e.g. some investigated hygrothermal performances of different designs, some mainly concerned the numerical simulations of heat and moisture transfer, some focused on hygrothermal properties of the ground, whereas others mainly concerned the thermal performances of the walls or energy loss of the basement. A detailed examination of the 22 particularly interesting studies revealed that several of them were related, either to the same research or to the same authors. Through a sorting process, involving a detailed examination of the studies, 10 of the newest or most comprehensive studies were selected for further review and subjected to scrutiny. A complete overview of the 22 interesting studies and the 10 selected for review is shown in Table A.2. The overall scientific legitimacy of each article and its origin were considered continuously throughout the selection process.

Table A.2
Overview of particular interesting studies identified and selection of the 10 included in results.

Country	Organisation/ University	Year	Author(s) &Title	Included in results	
Finland	University of Oulu and Tampere University	2019	**Fedorik, Heiskanen, Laukkarinen & Vinha** [35] *Impacts of multiple refurbishment strategies on hygrothermal behaviour of basement walls*	**X**	
Canada	University of Manitoba	2020	**Saaly, Bobko, Maghoul, Kavgic & Holländer** [38] *Energy performance of below-grade envelope of an institutional building in cold regions*	**X**	
	NRC	2011	**Saber, Maref & Swinton** [50] *Thermal response of basement wall systems with low emissivity material and furred airspace*		**Related**
		2010	**Saber & Swinton** [51] *Determining through numerical modeling the effective thermal resistance of a foundation wall system with low emissivity materials and furred - airspace* (much the same as Saber, Maref & Swinton 2011)		
		2006	**Swinton, Maref, Bomberg, Kumaran & Normandin** [41] *In situ performance evaluation of spray polyurethane foam in the exterior insulation basement system (EIBS)*	**X**	**Related**
		2001	**Maref, Swinton, Kumaran, Bomberg** [52] *Three-dimensional analysis of thermal resistance of exterior basement insulation systems (EIBS)*		
		1999	**Swinton, Bomberg, Kumaran, Normandin & Maref** [53] *Performance of Thermal Insulation on the Exterior of Basement Walls*		
	University of Waterloo	2007	**Uneo** [54] *Hygrothermal Behavior of Interior Basement Insulation*		**Related**
USA	Building Science Cooperation	2009	**Straube** [34] *Field Monitoring and Hygrothermal Modeling of Interior Basement Insulation Systems* (Measurements performed in Kitchener, Ontario, Canada.)	**X**	
		2010	**Smegal & Straube** [55] *Building America Special Research Project: High-R Foundations Case Study Analysis*		
Sweden /USA	Chalmers University of Technology & USA, Oak Ridge National Laboratory	2012	**Pallin & Kehrer** [38] *Hygrothermal simulations of foundations: Part 1: Soil material properties*	**X**	**Related**
USA	Minnesota	2012	**Kehrer, Pallin**, Harmon & Goldberg [56] *Hygrothermal simulation of foundations part 1, Soil Material Properties*		
		2015	**Goldberg & Harmon** [33] *Cold Climate Foundation Retrofit Experimental Hygrothermal Performance: Cloquet Residential Research Facility Laboratory Results*	**X**	
		2013	**Goldberg & Steigauf** [57] *Cold Climate Foundation Retrofit Energy Savings: The Simulated Energy and Experimental Hygrothermal Performance of Cold Climate Foundation Wall Insulation Retrofit Measures— Phase I, Energy Simulation*		**Related**
		2015			

(*continued on next page*)

Table A.2 (*continued*)

Country	Organisation/ University	Year	Author(s) &Title	Included in results	
			Harmon (Advisor: Goldberg & Huelman) [58] *The Hygrothermal Performance of Cold Climate Basement Walls Retrofitted with Insulation and a Water Separation Plane* (Much of the same as in (Goldberg & Harmon 2015)		
	Colorado	2003	**Deru** [39] *Model for Ground-Coupled Heat and Moisture Transfer from Buildings*	**X**	
	University of Washington	2007	**Emry, Heerwagen, Klippenhan & Steel** [59] *Measured and Predicted Thermal Performance of a Residential Basement*		
Sweden	Chalmers	2013	**Pallin** [36] *Risk Assessment of Hygrothermal Performance - Building Envelope Retrofit* (Pallin has cooperated with USA, Kehrer)	**X**	
Belgium	Catholic University of Leuven	2004	**Janssen, Charmeliet & Hens** [38] *The influence of soil moisture transfer on building heat loss via the ground*	**X**	**Related**
		2002	**Janssen, Charmeliet & Hens** [49] *The Influence of Soil Moisture in the Unsaturated Zone on the Heat Loss from Buildings via the Ground*		
Greece	Democritus University of Thrace	2009	**Zoras** [42] *A Review of Building Earth-Contact Heat Transfer*	**X**	

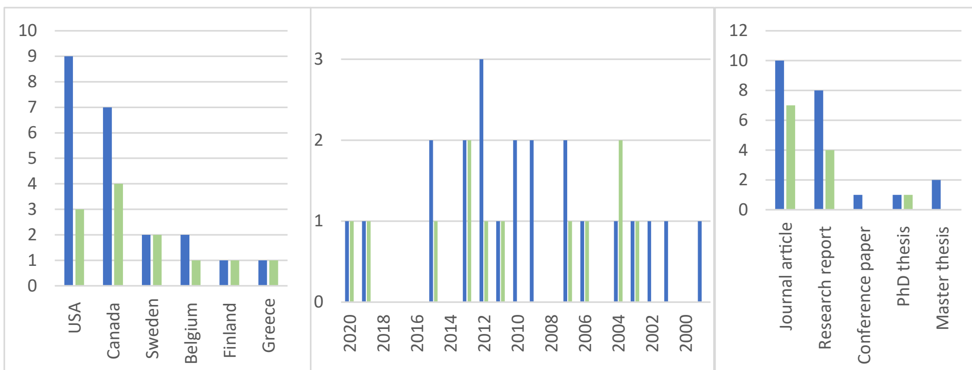

Fig. A.1. The 22 identified studies (blue) and 12 selected for further review (green) divided by country (left), year of publication (middle) and type of study (right).

Several limitations to the analysis have to be acknowledged:

- Including other search terms and additional search engines might have resulted in additional studies relevant to the scope of the study.
- The selection of relevant studies and identification of studies of particular interest are based on the main authors' subjective judgment.
- Several relevant studies might have been identified by performing citation chaining.
- The search was limited to research and review articles available online.

Although these limitations might have some bearing on the main outcome, their influence does not seem sufficient to significantly undermine the main conclusions presented in this article.

Appendix B. Identification and selection of studies focusing slabs-on-grade

An additional scoping literature study, focusing hygrothermal simulations of slabs-on-grade, was performed April 2021. The strategy for the selection of relevant studies was the same as for the initial search described in Appendix A, see Table B.1. First, 30 studies were selected from the review of the titles. Secondly, the studies were reviewed, and 17 particularly interesting studies were selected according to the following criteria: (1) they addressed hygrothermal simulations of slabs-on-grade, or (2) they covered three-dimensional effects related to heat loss from slabs to the ground. The 15 studies were reviewed and the two most relevant studies were selected for further review and subjected to scrutiny.

Table B.1
Identification of relevant studies and selection for review

Search engine/date	Search terms/ Limitations in the search engine	Selecting relevant studies			
		Results (sorted by relevance)	From review of titles	Particularly interesting studies concerning slabs-on-grade (References are not selected repeatedly)	Included in results
Science Direct (March 2021)	building AND moisture AND simulation AND ground AND (floor OR slab OR slab-on-ground)	3247	17 new (review of first 200 results)	Dos Santo & Mendes (2006) [44] Simultaneous heat and moisture transfer in soils combined with building simulation	Yes
	building AND moisture AND simulation AND ground AND soil AND (floor OR slab OR slab-on-ground)	2706	0 new	Rees, Zhou & Thomas (2001) [45] The influence of soil moisture content variations on heat losses from earth-contact structures: an initial assessment.	No, not as comprehensive as Janssen et al. (2004) [38]
	building AND moisture AND (slab OR floor) AND hygrothermal AND (ground OR soil)	375	0 new (review of first 50)	Rees, Zhou & Thomas (2007) [60] Ground heat transfer: A numerical simulation of a full-scale experiment	No, focus heat loss from a basement
					No, only heat transfer

(continued on next page)

Table B.1 (*continued*)

Search engine/date	Search terms/ Limitations in the search engine	Selecting relevant studies			
		Results (sorted by relevance)	From review of titles	Particularly interesting studies concerning slabs-on-grade (References are not selected repeatedly)	Included in results
	/ Limited to research articles and review articles			Zhou, Rees & Thomas (2002) [61] A numerical and experimental investigation of ground heat transfer including edge insulation effects.	
				Adjali, Davis & Rees (2004) [62] A comparative study of design guide calculations and measured heat loss through the ground.	No, only heat loss
				Adjali, Davies, Rees & Litter (2000) [63] Temperatures in and under a slab-on-ground floor: two- and three-dimensional numerical simulations and comparison with experimental data.	No, only heat loss
				Rees, Thomas & Zhou (2000) [64] Ground heat transfer: Some further insights into the influence of three-dimensional effects.	No, only heat loss
				Rees, Adjali, Zhou, Davis & Thomas (2000) [65] Ground heat transfer effects on the thermal performance of earth-contact structures.	No, only heat loss
				Thomas & Rees (1998) [66] The thermal performance of ground floor slabs—a full scale in-situ experiment.	No, only heat loss
				Yu, Kang & Zhai (2020) [67] Comparison of ground coupled heat transfer models for predicting underground building energy consumption.	No, only heat loss
				Weitzmann, Kragh, Roots & Svendsen [68] Modelling floor heating systems using a validated two-dimensional ground-coupled numerical model.	No, only heat transfer
Google scholar (January 2020)	building AND moisture AND simulation AND ground AND (floor OR slab) building AND moisture AND simulation AND coupled AND ground AND (slab OR floor) building AND moisture AND hygrothermal AND (slab OR floor) AND (ground OR soil) / Patents and quotes not included	42000 25700 4090	9 new (review of first 100 results) 0 new 1 new	Rantala & Leivo (2009) [43] Heat, Air, and Moisture Control in Slab-on-ground Structures	Yes
				Leivo & Rantala (2005) [69] Moisture behaviour of a massive concrete slab with a low temperature floor heating system during the initial drying period	No, Rantala & Leivo (2009) is included
				Wang et al (2018) [70] The effect of heat and moisture coupling migration of ground structure without damp-proof course on the indoor floor surface temperature and humidity: Experimental study	No, only experimental
Citing/related to	Dos Santos & Mendes (2006)		2 new	Libralato, Angelis & Saro (2019) [71] Evaluation of the ground-coupled quasi-stationary heat transfer in buildings by means of an accurate and computationally efficient numerical approach and comparison with the ISO 13370 procedure	No, quasi stationary
				Spiga & Vocale (2014) [72] Effect of Floor Geometry on Building Heat Loss Via the Ground	No, focus steady-state heat loss
Citing/ related to	Rantala & Leivo (2009) [43]		1 new	Leivo & Ralanta (2006) [73] Seasonal Changes in Water Content of Subsoil Beneath Old Slab-on-ground Structures in Finland	No – Rantala & Leivo (2009) is more comprehensive
Citing/ related to	Janssen et al. (2004) [38]		0 new		
			30	**17**	**2**

Several limitations to the analysis have to be acknowledged:

- Including different search terms or additional search engines might have increased the number of selected studies.
- The identification of relevant studies and selection of studies of particular interest are based on the main authors' subjective judgment.
- The search was limited to research and review articles available online.

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