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HYGROTHERMAL BEHAVIOR ANALYSIS OF CONSTRUCTION SYSTEMS APPLIED TO UNDERGROUND ELEMENTS IN HIGH WATER TABLES

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ABSTRACT

The moisture problems in buildings that present underground and semi-underground elements with high water table levels affect technical and economic decisions. This article shows several analysis of the mechanisms involved in moisture and heat transport, taking into account two different seasons, a rainy and a dry one, for the years of 2001 and 2002, in Brasília, Brazil, employing the WUFI 2D-3 program. Applying known data and program inputs, it was possible to present hygrothermal characteristics of the materials and variation of groundwater. The climate in Brasília, Brazil, was critical during the rainy season between January and March 2001, showing no significant differences between the dry seasons. There are significant changes in water content and relative humidity in the materials for water tables at 1,0 m deep, in soils as clay, sand and sand-clay, also presenting significant risk of fungal proliferation. The decision to implement a drainage system will depend on the water-level fluctuations in distinct periods of the year and on the soil type, hence the project designer shall dimension the drainage system considering lowering the water table at a minimum of 1,0 m in relation to the lowest elevation in buildings.

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INTRODUCTION

The presence of humidity in floors, curtains and walls in buildings with underground and semi-underground elements in high water table levels evoke several problems, including lesser thermal resistance, which provokes additional energy loss and increases degradation risks. In this context, it is important to study the influence of the groundwater level in typical construction systems employed in underground and semi-underground elements, considering the water-level fluctuations throughout the year in different positions and climate conditions, such as rainy and dry seasons, which are typical in the local of study, situated in the center region of Brazil (Mota, 2003; Pacheco, 2012). It is necessary to understand the hygrothermal behavior in which the referred constructions systems are inserted, so it can be possible to propose solutions that offer efficient protection, avoiding condensation, efflorescence and fungal proliferation, among several and distinguished pathological manifestations, common in this insalubrious condition. Another aspect that deserves attention is the construction cost of these types of solutions for infrastructure in typical soils at the center-west region in Brazil (Codeplan, 1984; Embrapa, 1978; Guimarães, 2002; Mota, 2003). Adriano et al. (2014) analyzed the excavation steps of apartment buildings in the central region of Brazil to describe the processes of underground water management which percolated through subsoil due to water table outcrops, showing that the costs incurred by the constructor for the foundation and containment engineering works in this case was 14% of the total development value, far superior to historical known values which varies from 3% to 5%. As a result of the increasing amount of constructions installed below the water table, the humidity phenomena in buildings has been recognized as a crucial factor that leads to anomalies capable to interfere with the habitability requirements of these constructions, translated into concepts such as watertightness, acoustic and hygrothermal comfort, among others, prescribed by the NBR 15575 (ABNT, 2013). About this concerns, highlighted water as the primary cause of a considerable amount of anomalies and secondary cause of many others, being the main cause of walls degradation since moisture infiltration search and find weak points (gap and voids) creating a net of preferential routes inside elements, usually throughout mortar joints. (Henriques, 1992; Jorne, 2010; Pinho, 2000; Magalhães, 2002; Torres, 2014). Given the importance of this theme, this work highlights the significance of understanding the mechanisms with which humidity is installed in underground and semi-underground elements, referring to the hygrothermal behavior in this type of building, during its useful life, evaluating the efficiency and inefficiencyof water table permanent lowering systems, employing a numerical tool to accomplish a vast range of numerical simulations (Borralho, 2013). The hygrothermal simulation program WUFI 2D-3 consists in an important tool which allows the comparison of moisture content profiles obtained numerically through simulations and the extrapolation of the systems efficacy in different configurations. The main goal of this article consists in analyzing the hygrothermal conditions of construction systems for underground and semi-underground elements in high groundwater levels, in different periods of the years 2001 and 2002, for clay, sandy and silty soil, taking into account the seasonal variation and the influence of the climate in Brasília, Brazil. The worldwide used software WUFI 2D-3 was employed to calculate the moisture and heat transfer in the proposed construction systems.

METHODS

Brazil's Climate Data Files: Brazil's climate data files were elaborated from hourly meteorological data provided by the Automatic Weather Station from Fazenda ÁguaLimpa – FAL, which belongs to the College of Agronomy and Veterinary Medicine – FAV of the University of Brasília[1]. The referred station is located at 1080 m Altitude, 15º56' S Latitude and 47º56'W Longitude. The climate aspects contained in the file used in the development of this work are: precipitation, external air temperature and relative humidity along the reference years of 2001 and 2002. In Brasília it is possible to observe two different seasons during each year, rainy and dry. The rainy season comprehends the months from January to May and from October to December, while the dry season occurs from June to September each year. The incident rainfall for each orientation is calculated from the precipitation value (amount of vertical rainfall), which is equal for all orientations. It is an aspect of the external climate that will also be used as an input for the numerous hygrothermal simulations. It is expressed in l/m².h, also varying depending on the orientation. The maximum values of the incident rainfall from the WUFI incident rainfall diagram are verified according to the incident rainfall index per azimuth. The average external temperature (expressed in Celsius degrees - ºC) and the external relative humidity (expressed in %) are fundamental aspects for the hygrothermal simulations calculus, used directly in the heat balance equation and indirectly in the moisture balance equation, presented by Jorne (2010). The climate data from Lisbon, Portugal, were obtained by simulation employing a WUFI 2D-3 program resource, Climate File Lisbon: FEUP University of Porto.

Characterization of the Studied Building: The constructive solution used in the simulations for the hygrothermal study was the conventional system employed in buildings with underground and semi-underground elements throughout the central region of Brazil since the 1960's. The construction was based on underground elements 3,68 m deep and ground floor with 3,80 m high ceiling. The underground structure was conceived in concrete curtain, impermeabilized externally, where it would receive the re-embankment local soil. A 20 cm thick floor and a 12 cm thick solid slab compound the other structures. At the ground floor, a double solid brick masonry interspersed with wind barrier insulation with 4 cm thickness was adopted, covered externally in 1,5 cm thick mortar and internally in 1,5 cm thick plaster, as indicated in Figure 1. The results obtained from analysis can be divided in masonry results (V1, V2 and V3) and concrete curtain results (V4 and V5) internally and externally, at the following highs: 0 m (top); 1,9 m, 3,8 m, 5,7 m (intermediate) and 7,6 m (bottom); slab results at L1 and L2 points at the center (0,75 m) and far end (1,5 m), respectively; and floor results at P1 and P2 points, at the center (0,75 m) and far end (1,5 m), respectively; as indicated in Figure 1. Tables 1 and 2 present characteristics of the construction solutions and adopted soils for the numerical analysis. The employed materials were obtained from the WUFI 2D-3 program data base. The sand-clay soil used in the analysis presents similar attributes to the sandy-clay soil surfaces found in the central region of Brazil, as shown by Mota (2003).

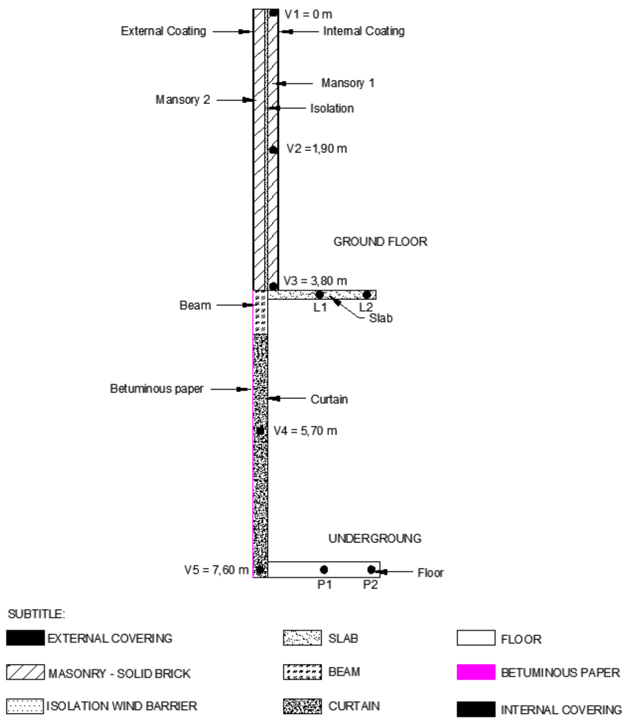

Figure 1 Generic Detail of the Constructive Solution

Coefficients R1 and R2 are used to estimate the amount of incident rainfall (l/m².h) on a surface for a given orientation and inclination, depending also of its geometry and location. Values for R1 are only related to the surface inclination. Values for R2 express the construction solution external surface exposure to the amount of rainfall. This exposure allows us to take into account the presence of neighbor buildings, vegetation or other types of elements (Jorne, 2010). The values for coefficient R1 were defined according to the construction system surface (vertical or horizontal) (Table 3). As for coefficient R2, the value of 0,07 s/m was adopted considering the reduced high of the building (less than 10 m high). The influence of neighbor buildings and vegetation was considered high. For the hygrothermal simulation, the inputs are presented in Tables 1 to 3. The simulation period comprehends the dry seasons (S1 and S2) and rainy seasons (C1 and C2) from the years of 2001 and 2002. For the internal environment conditions, we opted to define constant parameters at a 22ºC temperature and 62% relative humidity, values which are consistent to real local measurements.

Evalueted Parameters

Seasonal Influence: Aiming to observe the seasonal influence on the adopted construction system, years of 2001 and 2002, four different external climate seasons were studied, as follows: two rainy seasons (C1 and C2) and two dry seasons (S1 and S2). We opted to pin a constant material and geometry so that the only variable would be the external climate, thus allowing better interpretation of results. Also, we compared climate results from Brasília, Brazil, to external climate from Lisbon, Portugal. At this stage, soil type and characteristics were disregarded, accounting only the building external exposition. The climate conditions during rainy seasons in Brasília were more critical for C1, which presented average values for temperature at 21,5ºC and relative humidity at 75,3%, while C2 has shown values at 21,7ºC and 64,1% respectively. The dry seasons didn't present significant differences during the years of 2001 and 2002 in Brasília, showing average values for temperature at 20,6ºC and relative humidity at 63,0% for S1 and S2. The climate conditions were constant for all seasons studied in Lisbon, Portugal, when compared rainy seasons C1 and C2 and dry seasons S1 and S2, regardless the year, 2001 or 2002, showing average values for temperature at 18,3ºC and relative humidity at 65,1% for C1 and C2, and average values for temperature at 22,9ºC and relative humidity at 60,0% for S1 and S2.

[1]Estação Climatológica Automática da Fazenda Água Limpa (FAL) da Faculdade de Agronomia e Medicina Veterinária (FAV) da Universidade de Brasília (UnB), 2019. Disponível em:<http://www.fav.unb.br/86-faculdade-veterinaria/128-base-de-dados-estacao-automatica-dados-diarios> Acesso em: 11 out.2019.

Table 1. Dimensions and water content of layers and materials employed in the analyzed construction solutions

Position	Material	Dimension (m)		Initial water content of the material (Kg/m^3)
		Thickness (cm)	Height (cm)	
GroundFloor	Masonry 1 – solidbrick	14,0	380,0	190,0
	Isolation 1 – wind barrier (sd = 0,1 m)	4,0	380	-
	Masonry 2 – solidbrick	14,0	380	190,0
	External coating – mortar - layer 3 from 4	1,5	380	160,0
	Internalcoating 1 – plaster	1,5	380	400,0
	Slab – concrete	144	12	381,8
Underground	Beam – concrete	20,0	60	381,8
	Curtain – concrete	20,0	328	381,8
	Floor – concrete	150,0	20	381,8
	Bituminouspaper (#15 Felt)	0,1	388	-

Source: Mota (2003).

Table 2. Characteristics of the adopted soils

SoilProperties*	*Sandy Clay*	*Clay*	*Silt*	*Sand*	*Silt Clay*
Density (kg/m^3)	1400	1267	1387	1579	1396
Pore (m^3/m^3)	0,472	0,517	0,489	0,404	0,481
Calorificcapacity (J/KgK)	850	850	850	850	850
Thermalconductivity	0,378	0,288	0,361	0,505	0,289
WDRF**	50	50	50	50	50

*North America Data Base (WUFI 2D)
**Water Diffusion Resistance Factor for the dry material
A soil temperature of 15ºC was adopted to perform the numerical simulations.
Minimumtemperatureobtainedby Longo [17]
Fonte: AdaptfromWUFI 2D-3.

Table 3. Values for R1 Coefficient

Material	R1Value
Vertical surface (i=90º)	0
Horizontalsurface (i=0º)	1

Source: Jorne (2010)

Tabela 4. Initial conditions for the materials on WUFI-2D program

Material	Temperature (ºC)	RelativeHumidity HR (%)	WaterContent (Kg/m3)
Masonry – solidbrick	22	62	7,8
Isolation 1 – wind barrier (sd = 0,1 m)	22	62	0
External coating – mortar – layer 3 from 4	22	62	6,9
Internalcoating 1 – plaster	22	62	4,9
Slab, Beam and Floor – concrete	22	62	7,6
Bituminouspaper (#15 Felt)	22	62	0

Source: Author (2020).

Influence of Material Properties: Aiming to examine the influence of the materials properties for different highs reached by the moisture from the external wall, some simulations were carried out employing the WUFI-2D program for the previous defined points: masonry (V1, V2 and V3) and concrete curtain (V4 and V5), for material shown in Table 4. For the interior plaster layer, external mortar layer, solid brick and concrete, materials employed in these analysis, during the periods C1 and S1, it was possible to observe from the moisture storage curves that the relative humidity levels were set in an interval from 60% to 70%, anterior phase for the hygroscopic interval (HR = 95%) and far from reaching the capillary moisture saturation degree (HR = 100%). The water content was lower than 10 Kg/m³, near to the materials reference numbers, according to the storage moisture curve for each one of the materials and to Table 4, demonstrating that, in these cases, there is no possibility of condensation for the studied climate conditions.

Influence of Soil Content: Aiming to ponder the influence of humidity at 1,0 m deep of a sand-clay soil, in the presence of a water table at 1,0 m to the lowest line of the building, simulations were performed at 0%, 62% (same relative humidity in the interior) and 100% soil relative humidity, for the rainy season C1. The result showed that the masonry in solid brick (points V1 to V3), for soil relative humidities of 0% and 62%, presented a maximum of 4% in water content in relation to the total content of 190 Kg/m³ for the material saturation, while for relative humidity of 100% this value reached 77% in V3, remaining 4% in V1 and V2. The concrete curtain points (V4 and V5), at soil relative humidity of 62% and 100%, showed up to 79% water content in relation to the total content of 381,8 Kg/m³ for the material saturation, while at relative humidity of 0% this value was only obtained at the base point (V5). As for the internal relative humidity, the soil moisture variation at 0% and 62% didn't influence on the internal relative humidity for the masonry in solid brick at the points V1 and V2, but at 100% soil HR, it reached approximately 100% at point V3, as also observed for the concrete curtain at points V4 and V5 for all soil relative humidities studied (Figure 11). Concerning the concrete slab, it does not suffer any influence from soil moisture variation, regarding water content and interior relative humidity. Otherwise, the floor (P1 and P2), when in direct contact with the soil (no impermeabilization), presented water content almost the same (slightly higher) as the concrete saturation content for all relative humidities studied. Also, interior relative humidity reached 100%. With reference to the given information, a soil relative humidity of 0% was adopted for all analysis of the influence of the water table variation for the proposed system, at different seasons. Disregarding the soil relative humidity, it is expected that the construction system will only be under the influence of the water content due to the water table and of the internal and external relative humidity.

Hygrothermal Analysis and Results

Influence of the Water Level: To study the influence of water level, simulations were carried out considering different thickness for the soil layer, according to the water level position in relation to the lowest line of the building, as follows: 1,0 m; 2,0 m; 3,0 m; 6,0 m and 9,0 m, for the same rainy season C1. A sand-clay soil and construction system materials shown in Table 1 were adopted as initial conditions. Based on the results obtained, we recognize the existence of significant alterations on water content and relative humidity when the water level is at 1,0 m deep and close to the construction elements of the building. During the rainy season C1, a water content level of 280 Kg/m³ was found for floor points (P1 and P2) and for the base of the concrete curtain (point V5). It was also possible to observe the beginning of capillarity at the curtain base (V5). The water table level showed no influence on other concrete curtain points or on all masonry points (V1 to V4). The solid slab also remained unaltered. Similarly, the floor points P1 and P2 as well as the base curtain point V5 displayed relative humidity of 100%, reducing this value until 62% (interior relative humidity) for the remaining curtain points and all the masonry points (V1 to V3), finally reaching the slab, which suffered no influence from water table levels. For the remaining water table depths (2,0 m; 3,0 m; 6,0 m and 9,0 m), the influence of water content has low significance for masonry (V1 to V3), concrete curtain (V4 and V5), floor (P1 and P2) and slab (L1 and L2). The relative humidity for all points presented goes by 68%. In addition, for all levels of water table (1,0 m; 2,0 m; 3,0 m; 6,0 m; 9,0 m) during season C1, the construction system temperature was 22ºC, a similar value to the interior temperature adopted.

Influence of Seasonality: In order to study the influence of seasonality concerning the hygrothermal behavior, several simulations were performed for a sand-clay soil and a water level at 1,0 m deep in relation to the lowest line of the building, where the influence of water content was found to be significant. Simulations show the results of water content, relative humidity and temperature, for the different climate conditions: rainy seasons (C1 and C2) and dry seasons (S1 and S2), along the years of 2001 and 2002. It is clear the increase in water content, near to the saturation points of the materials in almost all the walls and floor during the rainy season C1, from January to May 2001. During the dry season S1, from June to September 2001, part of the masonry and concrete curtain (points V3, V4 and V5) and all floor (P1 and P2) were near to the saturation points of the materials, not getting into balance with the external environment, which remained at a high saturation level even during the dry period in 2001 and remained constant during all year of 2002. As for the slab (at point L1), it was observed a significant increase in water content and relative humidity at the end of the rainy season of 2001 (C1), which remained constant along the year of 2002. Based on the performed analysis, we witnessed that at the end of the rainy season in 2001 (C1), the construction systems which were directly in contact with the soil and the ones just above it presented a significant increase in water content and relative humidity. The moisture height reaches its maximum at the concrete curtain and remained constant along all year of 2002. At the beginning of the dry season in 2001 (S1), the moisture height reaches the base of the masonry wall, remaining almost identical during the rest of 2001 and all year of 2002.

The WUFI 2D-3 program only considers capillary forces. This means that the isolation barrier for wind protection installed to the surface tends to saturation, regardless of the brick thickness inputted at the program. Thus, the results obtained without the wind barrier also reached saturation, maybe for the fact that the surface drying potential was not enough to counterbalance the amount of water provided and absorbed by the base. According to results, there are risks of fungal proliferation in all constructive system due to the presence of water table at 1,0 m deep and to the exposure to the climate conditions, regardless the season, rainy or dry, and the period of the year, for 2001 or 2001 to 2002. During rainy e dry seasons in 2001, it is possible to recognize the risk of fungal proliferation in all constructive system due only to presence of a water table at 1,0 m deep. For depths from 2,0 m on, in the same climate conditions there will be no risk, because the system remains at relative humidity and temperature within the acceptable limits, showing low water content. It is important to emphasize that the impermeable layer (Bituminous Paper #15 Felt) at the external face of the concrete curtain did not protect it due to the high humidity content, since the mechanism of moisture fixation goes by capillarity. Capillarity forces work by the combined actions of surface tension and the absorption forces by the pores. In this case, impermeabilization would only show good results for rainfall infiltrated water, not being a good solution for situations in which there is a water table at 1,0 m deep, that requires vertical and horizontal subsoil drainage solutions.

Soil Type Influence: Five (05) types of soil were adopted for hygrothermal analysis: sand-clay, clay, silt, sand and silt-clay; their properties were obtained from the North America Data Base from the WUFI 2D-3 program. The same construction materials from previous analysis were considered for the rainy season C1 and dry season S1 (both from 2001), at a water level 1,0 m deep, depth in which the water content influence was found to be significant. Based on the performed analysis, we observed that in the end of the rainy season C1 the constructive system directly in touch with the soil with a water table 1,0 m deep was most affected when in clay, sandy or sand-clay soils. Clay soils possess larger specific surface, lower permeability and higher capacity of water retention, while sandy soils possess macro pores and high permeability, despite their low water retention. Silty soils, however, retain a little more water than sandy soils and are more impermeable, thus the time necessary to reach the floor is longer. Both clay and Sandy soils favor capillarity phenomena and in a period of three months water already reaches the floor (P1 and P2), the concrete curtain (V4 and V5), masonry with solid bricks (V1, V2 and V3) and he slab (L1 and L2), besides presenting high risk for fungal proliferation and construction degradation. In this manner, in cases with clay and sandy soils with superficial water table it is necessary to execute a good subsoil drainage system.

Conclusões

The climate conditions in Brasília, Brazil, were studied for the years of 2001 and 2002, and a comparison was made to the climate in Lisbon, Portugal. In Brasília, the rainy season between January and March 2001 (C1) was more critical, showing no significant differences between the dry seasons (S1 and S2) along the two years studied. As for Lisbon, Portugal, none of the seasons studied presented significant statistical differences for 2001 and 2002. Water content profiles, relative humidity and temperature were almost the same for the years of 2001 and 2002, during the analyzed seasons, rainy or dry, both when there was no water table and when there were water tables in similar depths. Stands out the fact that the climate conditions during rainy season C1 were more critical than during C2. For dry seasons S1 and S2 there were found no significant differences for the climate conditions in Brasília, Brazil. For the construction system proposed, including materials such as internal plaster coating, external mortar coating, solid brick masonry and concrete, there are no possibilities of condensation nor risk of fungal proliferation for the climate conditions during the rainy and dry seasons in 2001 (C1 and S1). This means that, without a water table or moisty soil in base of the proposed system, it is viable, turning it unnecessary any kind of intervention. Water table floating is directly influenced by the season, rainy or dry, corresponding typically to the characteristic seasons of the central region climate in Brazil. Different water table positions in the soil were studied (1,0 m; 2,0 m; 3,0 m; 6,0 m; 9,0 m) inputting a rainfall file. The adequate value of rainfall content inputted in the climate file was able to properly simulate the water table level, at the aiming depths, with no influence in the studied configuration for the considered materials properties. Hygrothermal Analysis for sand-clay, clay, silty, sandy and silt-clay soils from the North America Data Base – from the WUFI 2D-3 program, were carried out during the rainy (C1) and dry (S1) seasons. We concluded that, at the end of the seasons studied, the construction systems (floor, curtain, slab and masonry) in direct contact with the soil presenting a

1,0 m deep water table (in relation to the lowest line of the building) is significantly affected in clay, sandy and sand-clay soils. Clay and sandy soils favor the capillarity phenomena in the materials and present high risk of fungal proliferation in the construction systems. For depths from 2,0 m on, at the same climate conditions, there were no risks shown, the system remains at acceptable relative humidity and temperature, with low water content. The performed analysis didn't consider the soil re-embankment at the concrete curtain in the subsoil.

From this point forward, we present the conclusions obtained for the water table at 1,0 m deep in sand-clay soil, typical in the central region of Brazil:

- The major differences in water content profile and relative humidity happened during the initial months of the year 2001, from January to May, in the floor and at the base of the concrete curtain, while these differences become less evident when analyzing the hole period studied (2 years: 2001 and 2002);
- The moisture high reaches its maximum at the concrete curtain in March 2001. In the beginning of the dry season, in June 2001, it starts to reach the base of the masonry wall. Thereafter, the moisture high remains identical and constant along the years studied.
- It is also important to emphasize that the existence of an impermeabilizing layer of Bituminous paper #15 Felt at the external face of the concrete curtain didn't protect it because the humidity fixation mechanism functions by capillarity;
- The concrete floor also reached its moisture maximum at the end of March 2001, remaining unaltered along the rest of the studied period. Meanwhile, the concrete slab reached its maximum after six months at the region near the concrete curtain (L1), remaining unaltered at its central region (L2).
- The conditions in dry seasons S1 and S2 didn't allow a concrete and masonry material effective drainage, thus having no significant power to low the moisture high at the end of two years. Thus, in these situations it is absolutely necessary to perform subsoil drainages to assure the useful life of the proposed construction system.

It is important to state the significance of performing seasonal variation evaluations (water table fluctuations) in the tropical soils present in the central region of Brazil, once the decision of implementing a drainage system will depend on the fluctuations, which can compromise the durability of materials in rainy season when the projects don't consider the possibility of a 1,0 m water table in subsoils. According to this study, it is possible to conclude that for buildings implemented below the water table level, mainly in clay and sandy soils, the project designer shall consider for the subsoil drainage system that the trench lines connected to the draining bed have to be dimensioned in such a way that the phreatic line is lowered at minimum at 1,0 m deep from the bottom line of the building.

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