The ground surface energy balance in modelling horizontal ground heat exchangers

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Abstract. The performance of horizontal ground heat exchangers (HGHEs) is strongly dependent on climatic conditions, due to the low installation depth. In numerical modelling of HGHEs, the estimation of shallow soil temperature distribution is a key issue, therefore the boundary condition (BC) at the ground surface should be assigned carefully. With this in mind, a model of the energy balance at the ground surface (GSEB), based on weather variables, was developed. The model was tested as the 3rd kind BC at ground surface in modelling HGHEs by means of the FEM code Comsol Multiphysics, solving the unsteady heat transfer problem in a 2D domain. The GSEB model was calibrated and validated with the observed soil temperature at different depths. In addition, the effect on numerical solutions of different BCs, when assigned at the ground surface, was analysed. Three different simulations were carried out applying the GSEB model, the equivalent surface heat flux and temperature as boundary conditions of the 1st, 2nd and 3rd kind, respectively. The results of this study indicate that the use of the GSEB model is a preferable approach to the problem and that the use of the equivalent surface temperature can be considered as a reasonable simplification.

1. Introduction
Nowadays, the reduction of greenhouse gas emissions and the rational use of energy have become a major issue. Worldwide, the great opportunity for energy saving in the buildings sector has been recognised. For the above reasons, recent environmental policies have promoted the energy efficiency of buildings and the spread of renewable energy technologies. Among them, ground-coupled heat pumps (GCHPs) are regarded as a reliable technology and may represent an efficient solution for space heating and cooling, due to their high energy efficiency, if properly designed according to local environmental conditions [1-2].

In GCHPs, a ground heat exchanger is required to thermally couple a heat pump with the ground. The ground heat exchanger usually consists of a piping system installed in vertical boreholes or in shallow diggings. Vertically coupled heat pumps benefit from the relatively stable temperature in the deep ground and uses geothermal energy from the earth whereas a horizontally coupled heat pump uses the seasonal heat storage in shallow soil. As a consequence, the performance of horizontal ground heat exchangers (HGHEs) is strongly affected by the climatic conditions due to the low installation depth. The heat transfer will essentially depend on the temperature difference between the working fluid and the natural ground temperature at the average depth of the HGHE. The seasonal variation of the soil temperature at shallow depth can lead to unfavorable working conditions and, consequently, to
an efficiency reduction. Nevertheless, ground thermal drifts are not expected for shallow HGHEs, also after long-term operations, due to the energy balance at the ground surface [3].

The numerical modelling of HGHEs is a difficult task due to the need of an accurate prediction of the shallow soil temperature distribution, which results from the heat transfer occurring at the ground surface according to the local climate. A number of researches have been conducted to predict the performance of HGHEs, following an analytical approach based on the line source theory and cylindrical heat transfer equations [4] or, more recently, by means of numerical models. The annual variation of the soil temperature at different depths can be estimated using a sinusoidal function according to a correlation firstly proposed in [5], under the assumptions that the ground can be considered a semi-infinite solid, and that the surface boundary condition (BC) can be described by a sinusoidal temperature variation. This approach is frequently applied in modelling of HGHEs, were the complex heat transfer phenomena at the ground surface can be reduced to a 1st kind BC. A numerical model for horizontal pipes was developed applying an explicit finite difference scheme in [6], assuming a radially symmetrical temperature profile from inside the pipe, and a far-field BC based on the previously mentioned correlation [5]. A sinusoidal temperature trend was assigned to the ground surface also in [7]. A daily temperature time series was used as BC in [8], as calculated by means of a ground surface energy balance using real weather data. In [9], the surface temperature trend (1st kind BC) was converted to the equivalent heat flux at the ground surface (2nd kind BC), with the aim of considering the variation in the ground surface temperature due to the effect of the heat transfer by HGHE. Despite the long computational time required, numerical studies have been carried out including the mass transfer, in order to take into account the effects of the soil moisture content and migration [10]. Others applied a 3rd kind BC at the ground surface. In [11] only the convective heat flux between air and ground is considered. The external environmental conditions are included in the model by means of energy balance equation validated against experimental data, taking into account the effect of solar radiation, latent and sensible heat transfer in [12]. A earth-air tunnel in a ventilation system has been modelled including the simultaneous heat and moisture heat transfer at the ground surface [13]. On the other hand, a new approach to include the seasonal variation in soil temperature, which has been included as an internal source term instead of comprehensive energy balance at the ground surface, was recently proposed in [14].

The proper assignment of the boundary condition to the ground surface is important in order to carry out an accurate simulation of HGHEs. With this in mind, we proposed a model of the energy balance at the ground surface, which was implemented in the numerical code Comsol Multiphysics as the 3rd kind BC in modelling HGHEs [15]. This approach would allow a more reliable prediction of HGHE performance and moreover, to take into account of the ground surface temperature variation induced by HGHEs. This aspect is not considered with simplified BC (e.g. 1st kind BC). According to [15], this paper provides a further in-depth modelling of the heat transfer processes at the ground surface by improving the convective component of the energy balance by introducing the aerodynamic resistance of the canopy layer. The reliability of the proposed energy balance model has been tested against experimental data. Furthermore, we compared different boundary conditions at the ground surface in modelling HGHEs. The ground surface energy balance model (GSEB), the equivalent surface heat flux and temperature were assigned as boundary conditions of the 1st, 2nd and 3rd kind in three different simulations, respectively.

2. Methods

This study was intended to develop a simplified model of the energy balance at the ground surface, which could be used as a BC in numerical simulation of HGHEs. Moreover, three different approaches to the modelling of the heat transfer at the ground surface were tested (1st, 2nd and 3rd kind BCs) and then compared.

The software COMSOL Multiphysics V5.0, which is based on the finite-element method, was used to solve the 2D unsteady-state heat transfer problem in solids, thus, only conductive heat transport was considered. We developed a model of the energy balance at the ground surface, taking into account of
the ground surface properties (albedo and emissivity). A comprehensive weather data set based on experimental data (solar radiation, air temperature, relative humidity, atmospheric pressure and wind speed) was used for simulations. In order to calibrate and test the proposed GSEB model we carried out a preliminary comparison between the calculated and the observed soil temperature at various depths, showing a good agreement.

The GSEB model was applied as the BC at the ground surface in a simulation, which was carried out to analyse the energy performance of a HGHE in heating and cooling. In this study we simulated an innovative horizontal ground heat exchanger, called Flat-Panel, which has been developed recently at the University of Ferrara [16]. Finally, the GSEB model (3rd kind BC), the equivalent heat flux (2nd kind BC) and the equivalent temperature (1st kind BC) on ground surface were applied as boundary condition in three different simulations comparing the numerical solutions in order to identify the proper boundary condition in modelling of HGHEs.

2.1. Model domain
The FEM model was solved for a 2D model domain which comprises a Flat-Panel and a wide part of the surrounding soil (10 m long and 10 m deep). The domain was configured according to the experimental setup at the Department of Architecture of the University of Ferrara, which was equipped with 2 Flat-Panels [16]. The extent of the domain has been selected so that it was large enough to approximate an infinite medium. In the 2D model domain, the Flat-Panel was introduced as 2nd kind boundary condition and modelled as a vertical line, 1 m high and laid within shallow soil, between a depth of 0.9 and 1.9 m, as shown in Fig.1 together with the full mesh. Finally, a symmetric approach was applied to reduce the time required for calculations.

The soil is homogenous and isotropic over the entire domain, in agreement with many approaches to the modelling of HGHEs [17]. Here, the thermos-physical properties of the soil were chosen according to a preliminary field survey which was carried out at the experimental site [18] in order to obtain more reliable simulation. Overall, the soil was found to be a mixture of silt, sand and clay, with a large component of organic matter. In order to solve the energy balance equation at the ground surface, the surface albedo $\alpha$ and emissivity $\varepsilon$ (in the infrared) have been considered. The properties of the ground surface were taken for a bare soil according to [19]. The soil properties and that of the ground surface are reported in tab.1.

![Figure 1. Schematic of the 2D domain, mesh and boundary conditions.](image)

| Material properties |
|---------------------|
| **Thermal conductivity (W/mK)** | **Density (kg/m³)** | **Specific heat (J/kgK)** | **Surface albedo (⁺)** | **Surface emissivity (⁻)** |
| 1.40 | 1720 | 2000 | 0.15 | 0.95 |
The heat equation was discretized spatially over the numerical domain by the finite element method using triangular elements with quadratic weighting functions. A higher mesh resolution was set near the Flat-Panel BC and on the top edge of the domain (representing the ground surface) where higher temperature gradients are expected, and coarse in the outer part of the domain. In order to check the grid independence of the solution, a preliminary analysis has been carried out. Different grid refinements have been simulated, progressively increasing the number of elements in the vicinity of the Flat-Panel and of the top boundary, as well in the whole domain. The final mesh is composed of triangular linear with 27200 degrees of freedom.

2.2. Boundary conditions
Thermal boundary conditions were assigned to the outer domain boundaries only. The lower and vertical boundaries in the soil domain were assumed to be adiabatic. On the left vertical side this was due to the condition of symmetry. At the top boundary, representing the ground surface, a 3rd kind boundary condition (BC) has been assigned by means of GSEB model, as detailed in section 2.3. The Flat-Panel was treated as a time-dependent boundary condition by means of a heat flux time series, according to the calculated heating and cooling demand, as described in section 2.4. To run the GSEB model and to determine the HGHE heat flux at hourly scale, a complete set of 2014 weather data of Ferrara, a city in northern Italy, were used in simulations. Finally, in the further analysis, boundary conditions of 1st, 2nd and 3rd kind were imposed at the ground surface in three different simulations. The GSEB model was firstly used as the 3rd kind BC in a preliminary model to assess the equivalent heat flux (2nd kind BC) and the equivalent ground surface temperature (1st kind BC). The initial temperature distribution for simulations was obtained for the 1st day of 2014 from the available soil temperature data.

2.3. The modelling of the energy balance at the ground surface
In the numerical model, the heat is transferred only by conduction between the ground surface and the underlying soil. The temperature in the shallow soil depends on the energy fluxes at the ground surface, so the soil heat flux was defined by the ground surface energy balance equation for the infinitesimally thin surface layer (i.e. the interface between the ground and atmosphere), which can be written in his general form as a function of time and the surface temperature:

$$G(t, T_s) = R - H - LE$$  \hspace{1cm} (1)

where:
- $G$ = soil heat flux (W/m$^2$)
- $R$ = net radiative energy flux (W/m$^2$)
- $H$ = sensible energy flux (W/m$^2$)
- $LE$ = latent energy flux (W/m$^2$)

The magnitude of each component is a time-varying function, which depends on weather conditions; therefore, a complete set of weather data is required as an input for equation (1). The GSEB model was developed for grassy surfaces in order to have comparability with the available measurements of soil temperature at different depths. The experimental setup, taken as the reference [16], is covered by a wild meadow which is not subjected to regular watering and mowing. As suggested by [20-21], a detailed modelling of the effect of vegetation would require an additional equation to solve the energy balance in the foliage layer firstly, secondly the energy balance between vegetation and soil. However, these models require the knowledge of several parameters related to the type of vegetation, cutting cycles and irrigation, which are difficult to find. To reduce the computational time, a simplification in modelling the vegetation layer has been introduced by neglecting a separate energy balance equation for vegetation and the underlying soil. The effect of the former one was introduced in each component of the GSEB by means of appropriate correlations.

The radiative component mainly affects the surface temperature, particularly during the summer season. The net radiative flux $R$ (W/m$^2$) is the sum of the incident shortwave solar radiation into its
direct and diffused components (as absorbed and reflected by the surface) and on the longwave radiation received and emitted by the surface. The amount of shortwave and longwave solar radiation reaching the ground surface and the outgoing longwave radiation as well, are reduced by the shading due to the foliage layer. Moreover, the plant canopy absorbs long-wave radiation from the sky and re-radiates to the underlying soil surface. Consequently, a coefficient of shading \( s_f = 0.50 \) has been introduced similarly to FASST model [22]. This accounts for the actual surface coverage and for the mutual radiative heat transfer between vegetation and soil, which has not been solved here, contrary to the FASST model. The net radiative energy flux at the ground surface is given by:

\[
R = s_f ((1-a)R_s + R_{td} - \sigma \varepsilon_s T_s^4)
\]  

where:

- \( s_f \): calibration coefficient of shading
- \( a \): surface albedo
- \( R_s \): shortwave solar radiation (W/m\(^2\))
- \( R_{td} \): downward longwave solar radiation (W/m\(^2\))
- \( \sigma \): Stefan-Boltzmann constant (W/m\(^2\)K\(^4\))
- \( \varepsilon_s \): surface emissivity
- \( T_s \): surface temperature (K)

Aiming to simplify the former GSEB model [15] by eliminating the use of a calibration parameter, the convective heat flux between air and ground surface was calculated taking into account of the wind sheltering by the foliage layer, according to [23]:

\[
H = \rho_a c_a \frac{(T_a-T_s)}{r_a}
\]  

where:

- \( \rho_a \): density of air (1.205 kg/m\(^3\))
- \( c_a \): specific heat of air (1005 J/kg/K)
- \( T_s \): surface temperature (°C)
- \( T_a \): air temperature (°C)
- \( r_a \): aerodynamic resistance to heat transfer (s/m)

The aerodynamic resistance, \( r_a \) (s/m), is function of wind speed and canopy properties [24]. In this study, a reference a grass cover with a constant height of 0.12 m and a standardised height for wind speed, temperature and humidity of 2 m were assumed. In order to calculate the latent energy flux, the evapotranspiration \( ET_0 \) from the vegetated surface was calculated following the FAO Penman-Monteith model that proved to be reliable for different climates and time step [24]. The \( ET_0 \) is calculated for a reference grass crop, well irrigated and completely shading the ground. The evapotranspiration was calculated in terms of mass by assuming a constant density of water. A single crop coefficient \( K_c \) (0.25) which is usually provided for different agricultural crops and crop growth stages [24]) was introduced in calculating the latent heat flux, in order to take into account the characteristics of the vegetated layer (a not irrigated wild meadow). In our model, variations in vegetation have not been considered due to the objective difficulties in knowing the different growth stages of a wild meadow as well as the watering. In view of this, the latent energy flux at the ground surface is given by:

\[
LE = K_c \frac{\rho ET_0 l_h}{3600}
\]  

where:

- \( K_c \): crop coefficient
- \( \rho \): density of water (1.000 kg/m\(^3\))
- \( ET_0 \): reference evapotranspiration (l/m\(^2\)h)
- \( l_h \): latent heat of evaporation (J/kg)
The equation (1) was implemented in Comsol as a model variable. This represents the overall heat flux at the ground surface $G(t, Ts)$, which is a function both of time and surface temperature.

2.3.1. Comparison of simulation results and field data

The reliability of the GSEB model was tested with a preliminary simulation for a whole year. In this simulation, the heat load at the ground heat exchanger was neglected; therefore, the variation in the soil thermal field was only determined by the environmental conditions. A comprehensive data set of 2014 was managed to obtain several hourly scale time series that were needed as input in each term of equation 1. Several weather variables (solar radiation, air temperature, relative humidity, atmospheric pressure and wind speed) were measured by means of a weather station at the Department of Architecture in Ferrara. Measurements of the downward longwave radiation were provided by ARPA-EM, the meteorological service of the Emilia Romagna region. The simulated ground temperature trend was compared with the measured values at different depths (0.1, 0.8, 2.5 m).

The calculated daily average soil temperature is compared against measured values in fig. 2. Three temperature probes have been considered at three different depths (0.1, 0.8, 2.5 m respectively). The analysis of simulated and measured temperature time series showed that the model both over and under-predicts peak daily temperature near the surface, during different periods of the season. Deviations were clear mainly at shallow depths, where fluctuations in temperature are greater. The relationship between measured and simulated temperature was more stable in winter due to the low radiative heat flux and the negligible latent heat flux. In summer the model showed less accuracy, with a maximum difference of 3 °C at a depth of 0.1 m between calculated and measured temperature. The natural growth cycle of the grass covering the ground surface, which was not accounted in the model, may have played a role in varying the energy balance. However, the HGHE is usually installed at a depth between 1 and 2 m, where the daily fluctuations in soil temperature are reduced. The statistical uncertainty was calculated for the entire simulation period. For 2014, it was 0.99, 0.44 and 0.35 °C at a depth of 0.1, 0.8 and 2.5 m, respectively.

Scatter plots of the simulated soil temperatures versus the equivalent measured are shown in fig. 3 to a depth of 0.1 m and 0.8 m. In these graphs, the central line represents the optimum correlation between measured and simulated values, and the two others a span of 2 °C. In both cases the slope of the relationship is close to 1:1, although slight dispersion occurs when the soil temperature is higher than 20 °C.

The heat fluxes related to each component of the GSEB model are shown in fig. 4, for 7 days in winter and summer. Both in winter and in summer, the conductive heat flux in soil ($G$) shows a strong

Figure 2. Daily average temperature at different depth (0.1m, 0.8m and 2.5m). Continuous lines: simulated; broken lines: measured.
dependence on the net radiation (R), as a result of the partial shading of the ground surface by the vegetation above. The sheltering effect by the vegetated layer reduces the average convective heat flux (H). The low wind speed, representative of an urban area, furtherly reduces the convective heat flux. H is relatively stable and varies between +100 and -50 W/m$^2$ depending on the temperature difference between air and surface. Finally, the heat loss from the surface due to the latent heat flux (LE), which is strictly related to the air temperature and soil heat flux, is nearly zero in winter. An increase is observed in summer, with a daily oscillation between 25 and 5 W/m$^2$ during daytime and nighttime, respectively.

2.4. The energy loads for the ground heat exchanger

The energy requirement for space heating and cooling is defined as the amount of energy needed to maintain a constant target value of the building indoor temperature. In GCHPs, the thermal energy is extracted/transferred from/to the ground by means of the ground heat exchanger.

The modelling of the thermal behaviour of a building can be simplified with a lumped parameter approach by reducing the building to a resistance-capacitance model and taking into account the heat transfer through the walls, the thermal inertia of the building and the energy contribution by HVAC systems [25]. A simplified model, based on a lumped resistance-capacitance method, was applied in order to define an hourly energy requirement (both for heating and cooling) to be used in numerical simulation of Flat-Panels [26]. The transient temperature response of the building is determined by formulating an overall energy balance on the entire solid by relating the variation of the internal
energy to the rate of heat loss at the surface, according to the difference between the indoor temperature of the building and the outdoor air temperature. In this case the actual ambient air temperature of Ferrara for 2014 was simplified with two sinusoidal trends; on an annual and daily basis, respectively, as shown in fig. 5 together with the hourly heat load profile during winter. A detailed description of the model is reported in [18]. The energy demand has been calculated for a building with an overall transmittance of 0.5 W/m$^2$K, and a volumetric heat capacity of 100 kJ/m$^3$. The heating season is supposed from mid-October to April 15th; the cooling season from May 5th to the middle of September. In the model, the heating/cooling system was set to operate to maintain a set point indoor temperature (20 °C in winter and 24 °C in summer). A time schedule was assumed to simulate actual working conditions for a residential building in a mild climate: 4 - 11 AM and 6 - 12 PM during working days, and 6 AM to 12 PM on the weekends. Furthermore, it has been assumed that the heating and cooling power of the system could not exceed 50 W/m$^3$ of the building when it is turned ON. The daily energy demand (at the Flat-Panel) for both heating and cooling is reported in fig. 6. Under the assumed conditions, the space heating/cooling system worked for a total of 2728 h in heating mode; only 792 h in cooling mode. The calculated energy demand for 2 m$^3$ of building has been supposed to be the full energy requirement for the geothermal closed loop, therefore the resulting heat flux time series (W/m$^2$) has been directly applied as the boundary condition at the Flat-Panel in the numerical model. As a result, the maximum heating and cooling heat flux at the ground heat exchanger was 100 W/m$^2$. On overall terms, during the heating season a total amount of 36.4 kWh (i.e. 72.8 kWh according to the symmetrical domain) for each metre of Flat-Panel have been extracted from soil for 190 days; during cooling season it was 21.8 kWh (43.6 kWh) 145 days.

**Figure 5.** Hourly ambient air and building heating power time series.

**Figure 6.** Energy requirements for space heating and cooling at the HGHE.
3. Results and discussion

A comparison between the numerical solution by setting 1\textsuperscript{st}, 2\textsuperscript{nd} BCs and the enhanced GSEB model (3\textsuperscript{rd} kind BC) at the ground surface is here presented, similarly to [15]. A preliminary simulation was run using the GSEB model as the ground surface BC; then the equivalent heat flux and the equivalent surface temperature were obtained. A complete set of weather data of Ferrara for 2014 has been used and the soil temperature profile for the 1\textsuperscript{st} day of 2014 was set as the initial condition. The operation of Flat-Panel was simulated in three new simulations with the proposed GSEB model, the equivalent heat flux and ground surface temperature as BCs, respectively.

The results are compared in terms of the average temperature at the HGHE wall surface which be considered as the temperature at the interface between the ground and the Flat-Panel surface, according to the simplifications and assumptions considered. This temperature is representative of the HGHE performance with the different BCs at the ground surface. Moreover, the temperature in the surrounding soil has been calculated to evaluate the effect of the heat transfer induced by the Flat-Panels.

The resulting time series for each BCs of the daily average temperature at the HGHE wall are shown in fig. 7. In the graph, a whole year is presented, starting in May, when the cooling season begins. The maximum temperature is reached in all three cases in August, according to heat released to the ground. The temperature follows a similar trend in the case where the GSEB and the equivalent temperature are assigned as BC. With the equivalent heat flux, the Flat-Panel surface has a maximum value 1.2 °C higher than the other cases. In the HF case, the thermal drift continues until the beginning of the winter season. The minimum in the temperature trend (at the middle of February in all three cases) is delayed of 45 days in comparison with the temperature at the ground surface and that of the air. When the equivalent heat flux is assigned to the surface (case HF) the temperature decreases more rapidly. The maximum difference is of 1.2 °C in comparison to the other two cases on a daily average basis. A thermal drift of 1 °C is detected after a year in the case HF, because the equivalent heat flux, which was calculated without the HGHE operating, does not balance the energy demand of HGHE. By contrast, a slight discrepancy is calculated between the case GSEB and T. This results confirms that the use of 1st kind boundary conditions could be considered an acceptable simplification, according to our previous findings.

In fig. 8, a weekly detail of the hourly HGHE operation, when the minimum temperature at the Flat-Panel surface is reached in the heating period. According with the above considerations, temperature values are significantly different in the case of equivalent heat fluxes; therefore the effect of energy extracted or released is over-estimated. In the other two cases the differences, though present, are negligible.

![Figure 7. Daily average temperature on the HGHE surface for the three BCs.](image-url)
Finally, the hourly time series of soil temperature at two different points in the soil domain are shown in fig. 9. A temperature probe is positioned at the average depth of the HGHE (-1.5 m) and 0.5 m in front of it, while the other is above the HGHE, 0.8 m deep in soil. The calculated maximum difference between the case HF and the two other cases is 1.4 °C above the exchanger. Furthermore, a significant thermal drift is maintained over the entire year. By contrast, the soil thermal field is comparable for GSEB and T, similarly to the temperature at the HGHE wall.

4. Concluding remarks
This paper is focused on the improvement of the energy balance at the ground surface model (GSEB) which was implemented in COMSOL Multiphysics to be tested as boundary condition at ground surface. The model requires the ground surface properties and a comprehensive weather dataset for simulations. The results of simulations carried out with the GSEB model were compared with the observed soil temperature data at different depths in 2014, proving to accurately predict the temperature in the soil. Moreover, the effect on numerical solutions of different boundary conditions at the ground surface was analyzed in modelling HGHEs, solving the unsteady heat transfer problem in a 2D computational domain.

**Figure 8.** The hourly average temperature at the HGHE surface during a week of operation.

**Figure 9.** Average temperature in the soil for three boundary conditions.
Simulations were carried out to test the HGHE energy performance in heating and cooling, under the same environmental conditions. The GSEB model, the equivalent heat flux and temperature at the ground surface were used as boundary conditions (BC) of the 1st, 2nd and 3rd kind in simulations.

The solution of the equivalent heat flux at the ground surface is significantly different from the other two cases, and should be considered as a precautionary approach. On the other hand, when a boundary condition of the 1st kind (i.e. equivalent surface temperature) is used, a significant constraint is imposed to the surface temperature, which is not allowed to vary due to the heat transfer by HGHE. However, the correct estimation of the surface temperature is of great importance also in this case, and a preliminary simulation with a GSEB could be required. Consequently, a preferable approach to the problem is the setting of a 3rd kind boundary condition (i.e. the GSEB model), which not affects the calculation time. A correlation between ground surface and air temperature could be developed in the future to determine more quickly a feasible boundary condition in modeling HGHEs.

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