Study on the Heat Load Characteristics of Underground Structures
Part 1. Field Experiment on an Underground Structure under an Internal Heat Generation Condition

Kyung-Soon Park*, Hisaya Nagai and Takeshi Iwata

1 Graduate Student, Department of System Engineering, Graduate School of Engineering, Mie University, Japan
2 Associate Professor, Department of Architecture, Faculty of Engineering, Mie University, Japan
3 Research Engineer, Department of Architecture, Faculty of Engineering, Mie University, Japan

Abstract
This study is being conducted to clarify the heat load characteristics of underground structures. The authors have sought to achieve this by clarifying the heat and moisture behavior of an underground basement and surrounding ground, and acquiring basic data for computational analysis. This paper presents measurement results acquired over approximately one year of field experiments on an underground experimental basement under internal heat generation conditions, commenced in October 2004. The authors also present the results of analyses on the heat and moisture behavior of the experimental basement and ground, the influence of internal heat generation on the surrounding ground, the condensation behavior, the interrelationship between precipitation and the fluctuation of moisture content in the ground, the annual mean heating load per unit area, and other factors.

Keywords: underground structure; heat and moisture behavior; internal heat generation; moisture content; condensation

1. Introduction
A number of underground structures have recently been constructed to make effective use of land, to conserve energy, and so forth. From the perspective of the thermal environment, there is a need to precisely evaluate the heat and moisture behavior of underground basements and the surrounding ground.

The ground and concrete are generally porous mediums affected by moisture to some degree. Moisture is one of the main components of the thermal environment in underground structures and the surrounding ground. The moisture in the ground and concrete has a great influence on the surrounding area. Further, the moisture content of the ground and concrete is strongly influenced by the precipitation and depth of the water table in the ground. For this reason, the moisture content profiles in the ground and concrete need to be predicted in order to precisely consider the heat transfer in underground structures.

Moisture strongly affects heat transfer, and the heat and moisture transfers in a porous medium are coupled phenomena (Matsumoto, 1978). The effect of coupled phenomena is also non-linear process because of the sensitive variation of physical parameters with moisture content and temperature. Thus, this effect needs to be treated as a coupled non-linear problem (Matsumoto, 1984). Many studies have investigated simultaneous heat and moisture transfer in porous mediums (Matsumoto et al., 1988).

A number of studies have been conducted on the thermal properties and heat load calculations of underground spaces. Hasegawa et al. (1992) measured the temperature of a semi-underground basement and evaluated its thermal performance. Mitalas (1987) proposed a simple heat load calculation method for three kinds of basement (deep, shallow, and slab on grade). Sobotka et al. (1995) analyzed deep basement heat loss by measurement and calculation.

In all of these studies, however, the load calculations and evaluations of the heat environments treated the heat transfer in the ground as simple heat diffusion. The influence of moisture was not sufficiently considered. None of the simple methods for heat load calculation have incorporated the influences of moisture and precipitation with sufficient generality or accuracy.

There were thus two main purposes of this study: first, to actually measure and analyze the heat and moisture behavior of an underground basement and surrounding ground through a long-term field experiment; second, to develop a simple heat load calculation method incorporating the influences of moisture, precipitation, and so on.

This paper presents measurement results and details on an experimental underground basement...
and surrounding ground kept under an internal heat generation condition. The measurement results presented were collected through one-year of field experiments.

2. Outline of the Experiment
2.1 Experimental basement
The experimental site was located in Tsu, a city in central Japan. The basement was constructed in 1997 without any form of air-conditioning. As the temperature was thus left unadjusted, the basement presumably had little influence on the heat and moisture environment of the surrounding ground.

The site plan, floor plan, and sectional plan of the experimental basement are shown in Figs.1 to 3. The basement measured 3.5m × 2.0m × 2.0m (see Figs.2 and 3), with a floor area and volume of 7m² and 14m³, respectively. Once the basement was installed underground, the roof was at a depth of 1.0m below the ground level. To clarify the influences of moisture from the ground, the wall of the basement was constructed with reinforced concrete untreated by any form of waterproofing or moisture prevention processing. The thicknesses of the ceiling/sidewall and floor were 0.25m and 0.3m, respectively, and blinding concrete and crushed stone were additionally paved below the floor level to a thickness of 0.3m.

To suppress the influences of thermal turbulence from the outside as much as possible, the entrance of the basement was insulated from heat by a 10cm-thick foam polystyrene board during the experiment. The ventilation was adjusted with a variable-air-volume fan set up in the upper part of the exhaust cylinder (See Fig.3.). The underground water table at the site was located at a depth of about 3m from the ground level. To keep the floor level higher than the underground water table and to keep the basement completely underground, the basement was banked by about 1m. The soil was banked from each sidewall of the basement to a distance 8m in a horizontal direction.

2.2 Measurement
Fig.4. indicates the measurement points in the basement. Table 1. lists the conditions measured and the devices used to measure them. Fig.5. shows the points where the temperature and water chemical potential were measured in the surrounding ground. The noughts and crosses shown in the surrounding ground in Fig.5. indicate the points for measurement of the temperature and water chemical potential, respectively. A thermocouple and hygrometer were installed in the instrument shelter to measure the outdoor air temperature and relative humidity. A pyrheliometer and albedometer were set up on the upper part of the ground level to measure the solar radiation and absorption ratio. The ground surface in the experimental location was kept bare during measurement. The fluctuation of the underground water table was measured using a water-level gauge placed in a well that had been dug at the experimental site.

2.3 Experimental conditions
The experiment was commenced on October 22, 2004 with the goal of clarifying the heat and moisture behavior of the basement and surrounding ground under an internal heat generation condition.

The indoor air temperature and ventilation rate of the basement during the experiment were set to 22°C and 2.2 times per hour, respectively. The indoor air temperature was controlled using an electric hot-air heater regulated by thermostat, and the ventilation was controlled using the variable-air-volume fan mentioned above. The indoor air humidity was not controlled.

The ventilation rate in this study was calculated by the vibration decay method of the carbon dioxide concentration. Results from a number of similar experiments performed periodically confirmed that the ventilation rate was steady during the measurement period. Further, a regression analysis confirmed that the ventilation rate was uncorrelated with the wind velocity, wind direction, and the difference between outdoor and indoor air temperatures. The precipitation, wind velocity, and wind direction were recorded automatically at 5-minute intervals and the other data were recorded automatically at 1-minute intervals.

3. Ground Characteristic
According to the exploration of three bores at points Table 1. Conditions Measured and Measurement Devices

| Conditions measured                  | Measurement devices          | Location          |
|--------------------------------------|------------------------------|-------------------|
| Outdoor air temperature and humidity| Thermocouple and hygrometer | Instrument shelter|
| Indoor air temperature and humidity  | Thermocouple and hygrometer | Basement          |
| Solar radiation and absorption ratio | Pyrheliometer and albedometer| Upper part of the ground |
| CO₂ concentration                   | CO₂ densitometer             | Basement          |
| Electric consumption                | Wattmeter                    | Basement          |
| Underground water table             | Water-level gauge            | Well for measurement |
| Wind velocity, direction, precipitation | Anemoscope, anemometer and rainfall meter | Vicinity of the experiment area |

| Temperature in/on the ground | Thermocouple | Location |
|-----------------------------|--------------|----------|
| (See Fig.1)                 |              | Depth from ground level [unit: m] |
| A1, B1, B2                  | 0.5, 1.0, 2.0, 3.0 |
| A2, A3, A4, A5              | 0, 0.05, 0.1, 0.5, 1.0, 2.0, 3.0, 4.0 |
| C                           | 0.7          |
| A1                          | 1.0          |
| A2, A4, B2                  | 0.1, 1.0, 2.0, 3.0 |
Nos. 1, 2, and 3 shown in Fig.1., the composition and distribution of the soil around experimental location are thought to be almost the same in both the horizontal and perpendicular directions. Fig.6. shows the moisture characteristics of three types of soil measured by Jury (1973) and the moisture characteristics measured in the samples. Sample A was taken from the vicinity of the ground level near the basement and sample B was taken from the vicinity of the ground level at a distance from the basement. The measurement results suggest that the experimental area is plain field sand.

4. Experimental Result

This chapter presents the results of measurements of the basement and surrounding ground taken from October 22, 2004 to October 31, 2005. The four-day omission in the measurement data was the result of a power failure from February 11 to February 14, 2005.

4.1 Outdoor climate

Figs. 7 to 10. show the outdoor air temperature, relative humidity, precipitation, and solar radiation for the measurement period. Table 2. lists three sets of figures for comparison: values measured at the
site, values measured at a nearby meteorological observatory, and values for an ordinary year in the region. Data on solar radiation are not given, however, as the meteorological observatory performed no measurements of this condition.

4.2 Precipitation and underground water table

Fig.11. shows the annual variations of the underground water table and precipitation. The maximum precipitation and the lower depth of the underground water table were 29.0mm/h (70.5mm/day) and GL-373cm, respectively. The depth of the annual mean underground water table was GL-445cm. The variation caused by rainfall was the only notable variation in the underground water table to result from factors such as periodic changes. On this basis, we concluded that the fluctuation of the underground water table had no direct repercussions on the basement floor.

4.3 Solar absorption ratio

The solar absorption ratio on the ground level was calculated from the pyrheliometer and albedometer measurements. Fig.12. shows the annual variation of the solar absorption ratio on the ground level. The daily solar absorption ratio during the measurement period changed from 0.69 to 1.0, and the solar absorption ratio rose markedly after rainfalls. These rises in the solar absorption ratio were attributable to the decrease in the solar reflection ratio by the wetting of the ground level during the rainfalls. The annual mean solar absorption ratio on the ground level was 0.84 (standard deviation 0.076).

4.4 Indoor air temperature and humidity

Fig.13. and Table 3. show the annual temperature variation of each measurement point on the inside
wall of the basement (See Fig.4.). The influence of the outside climate pushed the temperature amplitude on the ceiling and the corner of the upper part of the wall to levels higher than that on the other parts of the wall. The annual temperature amplitude on the corner of the wall, the thermally weak part, was therefore large due to the relatively low annual average temperature. Moreover, no differences in azimuthal temperatures were found in the central parts of the walls (N, S, E, W points).

Fig.14. shows the annual variation of the daily mean indoor air temperature of R1-R6 and analyzes the distribution. The maximum temperature differentials among the six measurement points in the horizontal and vertical directions were 1.5°C and 1.8°C during the heating period and 1.0°C and 3.0°C during the non-heating period, respectively. However, in light of the short generation time and the low mean temperature differential between the horizontal and vertical directions (1.0°C or less), the average value of the six points was used as the indoor air temperature for the subsequent analysis.

Fig.15. shows the daily variations of the indoor and outdoor air temperatures along with the electric consumption on a typical day during the heating period. The variation of the indoor air temperature and electric consumption by the electric hot-air heater in Fig.15. was attributable to the on/off control of the thermostat. The range of this variation remained almost constant throughout the entire heating period.

Fig.16. shows the annual variation of the daily mean indoor and outdoor air temperatures. The mean indoor air temperatures for the heating and non-heating periods were 21.7°C and 23.6°C, respectively, and the annual mean temperature was 22.2°C. On this basis, we concluded that the experimental indoor air temperature was successfully controlled.

Fig.17. shows the annual variation of the relative humidity of the indoor and outdoor air. The annual mean relative humidity of the indoor air was 51%, and the mean relative humidities for the heating and non-heating periods were about 35% and 75%, respectively. In the absence of any measures to control moisture in this experiment, the relative humidity of the indoor air fluctuated sharply between the heating and non-heating periods.

Fig.18. shows the annual variation of the water vapor pressure of the indoor and outdoor air. The daily amplitude of the vapor pressure of the indoor air followed that of the outdoor air during the heating period, but not during the non-heating period. This trend was attributable to the differential between the water vapor pressure of the outdoor air and saturated vapor water pressure of the indoor air. The former suppressed the rise of the latter, and the moisture evaporation on the inner surface of the wall suppressed the fall of the latter when the former rose.

Fig.19. shows the variation of the saturated water vapor pressure of the wall surface and the water vapor pressure of the indoor air. The condensation on the inner surface of the basement wall could not be visually confirmed during the measurement period. However, noting that the relative humidity of the indoor air was higher than that of the outdoor air from June to August (see the dotted line in Fig.17.), we compared the water vapor pressure of the indoor air and the saturated water vapor pressure on the inner surface of the wall in order to analyze the aspects of condensation. We concluded, based on this comparison, that condensation could not have developed on the other walls where the saturated water vapor pressure exceeded the water vapor pressure of the indoor air. We also judged, however, that condensation was very likely to have appeared for a period of about a month on the edge of the floor at the point where the behavior reversed. In other words, when the indoor air relative humidity of the basement was maintained at 90% or higher, most of the condensation was probably generated on the edge of the floor. This compels us to consider moisture control or latent heat load control in order to maintain a comfortable indoor environment.

4.5 Amount of electric consumption

Fig.20. shows the monthly average outdoor air temperature and the monthly integral electric consumption of the electric hot-air heater. The annual electric consumption was 2082kWh, and the maximum monthly and daily electric consumptions were 385.94kWh and 13.61kWh, respectively. All of these measurements were taken in January. In addition, the annual mean heating load per unit area of the basement was about 58W/m² (including about 19 W/m² by ventilation). This is 1/4 of the heating load per unit area for the ground building which corresponded to the basement. No cooling load (sensible heat load) was generated throughout the year.

4.6 Heat and moisture behavior of the surrounding ground

Fig.21. shows the annual variation of the daily mean ground temperature near the ground level (5cm in depth). The average temperature at the ground level, mean soil-air temperature, and mean outside air temperature were 17.3, 20.3, and 16.4°C, respectively.

| Mp | C | F | N | S | E | W | C1 | F1 | E1 | E2 | E3 | E4 | E5 | E6 | E7 | I | O | Indoor | Outdoor |
|----|---|---|---|---|---|---|----|----|----|----|----|----|----|----|----|---|---|--------|--------|
| Max | 25.9 | 23.2 | 24.2 | 24.6 | 24.1 | 24.4 | 25.5 | 23.0 | 25.6 | 26.0 | 26.3 | 24.1 | 22.6 | 22.6 | 22.4 | 30.1 | 25.0 | 24.5 | 36.0 |
| Min | 18.8 | 19.1 | 19.2 | 19.4 | 19.0 | 19.0 | 18.6 | 18.9 | 17.8 | 17.6 | 17.4 | 18.4 | 18.8 | 18.7 | 18.1 | 1.9 | 20.5 | 20.2 | 1.3 |
| M  | 21.7 | 20.9 | 21.4 | 21.5 | 21.3 | 21.3 | 21.5 | 20.7 | 21.2 | 21.2 | 21.1 | 21.1 | 20.5 | 20.5 | 20.2 | 16.5 | 22.4 | 22.2 | 16.4 |
| A  | 3.6 | 2.1 | 2.5 | 2.6 | 2.6 | 2.7 | 3.5 | 3.5 | 3.1 | 3.9 | 4.2 | 4.5 | 2.9 | 1.9 | 2.0 | 2.2 | 14.1 | 2.3 | 2.2 | 14.7 |

Note: The value of Max and Min listed in this table is daily mean value during measurement period.

Mp: Measurement Point (See Fig. 4), Max: Maximum value, Min: Minimum value, M: Annual mean temperature, A: Annual amplitude=(Max-Min)/2
for the year. The temperature near the ground level fluctuated by about as much as the temperature of the outdoor air.

Figs. 22 and 23 show the annual variation of the ground temperature at points A2 and A5 (See Fig.1).
Table 4. lists the annual amplitudes and annual mean temperatures at every measurement point, measured at each depth. The daily amplitude of the outdoor air ceased to have influence from depths of 0.5m onward. Moreover, the amplitude fell and the delay in the phase increased at progressively greater depths. As shown in Figs.22. and 23. and Table 4., the annual amplitude of the measurement point located farthest away from the outside wall of the basement exceeded that of the point nearest the basement, and the annual mean ground temperature approached the annual mean outdoor air temperature as the distance from the basement increased. These findings resulted from the heat generated internally within the basement, an influence which increased temperatures outward to about 4.0m from the outside wall of the basement.

Fig.24. shows the annual variation of the moisture content. The values were converted from the measurement values of the water chemical potential in the ground using the moisture characteristic curve of plain field sand, assuming that the equilibrium relationship between the moisture content and water chemical potential was not dependent on temperature. The moisture content of the ground at all depths rose during rainfalls and decreased after the rains. The tendency was most conspicuous at the shallow depth of 0.1m. Moreover, the variations of the moisture content at depths of 2 and 3m remained almost stable.

Table 4. Annual Amplitudes and Annual Mean Temperatures of the Surrounding Ground

| D1 [m] | M [°C] | A2 | A3 | A4 | A5 | B1 | B2 |
|--------|--------|----|----|----|----|----|----|
| 0.5    | 19.5   | 19.1| 18.2| 18.3| -  | -  | -  |
| 1.0    | 20.5   | 19.4| 18.6| 18.2| 19.4| 18.2| -  |
| 2.0    | 21.3   | 19.4| 18.7| 18.0| 19.5| 18.3| -  |
| 3.0    | 20.7   | 19.4| 18.5| 17.7| 19.1| 18.0| -  |
| 4.0    | 19.6   | 18.9| 18.0| 17.5| -  | -  | -  |
| A [°C] | 6.6    | 8.1 | 8.9 | 9.5 | 7.2 | 9.0 |
|         | 3.7    | 5.3 | 5.7 | 6.3 | 4.5 | 6.0 |
|         | 2.6    | 3.3 | 4.2 | 4.7 | 3.0 | 4.2 |
|         | 1.9    | 2.4 | 3.4 | 3.6 | -  | -  |

(Mp: Measurement Point, D1: Distance from the outside wall, D2: Depth from the ground level, M: Mean annual temperature, A: Annual amplitude)
throughout the entire year. We thus confirmed that the moisture content varied more drastically near the ground level, where the influences of precipitation and solar radiation were substantial. As the depth from the ground level increased, however, the moisture content remained progressively more stable behavior throughout the year.

In view of these findings, the fluctuation band of moisture content in the ground is thought to be strongly affected by precipitation but only weakly affected by the depth of the underground water table.

In the horizontal direction, however, we find that a simple comparison of moisture content is inadequate, given that only point C differs in the measurement depth. In this case we observed a changing tendency in the order of C, A2, and A4. On this basis, we concluded that the moisture accumulated in the ground of the upper part of the ceiling and flowed onto the outside wall of basement.

5. Conclusions

We conducted a field experiments to evaluate the heat and moisture behaviors of an underground basement and surrounding ground under an internal heat generation condition. This paper has presented the details of the experiment and analyzed the results. The main conclusions are as follows.

1) The outdoor air temperature and precipitation of the measured year were higher and lower than an ordinary year, respectively. The annual mean solar absorption ratio on the ground level was 0.84 during the experimental period (standard deviation 0.076).

2) The lower depth of the underground water table was GL-373cm, and the annual mean depth was GL-445cm. Thus, the fluctuation of the underground water table was not found to have direct repercussions on the basement floor. Moreover, the variation caused by rainfall was the only notable variation in the underground water table to result from factors such as periodic changes.

3) The mean indoor air temperatures for the heating and non-heating periods were 21.7°C and 23.6°C, respectively, and the annual mean temperature was 22.2°C. On this basis, we concluded that the experimental indoor air temperature was successfully controlled. The annual electric consumption of the electric hot-air heater was 2082kWh, and the maximum monthly and daily electric consumptions were 385.94kWh and 13.61kWh, respectively (all of these measurements were taken in January). The annual mean heating load per unit area of basement was about 58W/m² (including about 19 W/m² by ventilation). No cooling load (sensible heat load) was generated throughout the year.

4) The annual relative humidity of the indoor air was 51%. In the absence of measures to control moisture in this experiment, however, the relative humidity of the indoor air fluctuated rather sharply throughout the year. When basements are planned in highly humid regions, measures for the control of the moisture or latent heat load need to be considered in order to maintain a comfortable indoor environment.

5) The condensation on the inside wall surface of the basement could not be confirmed by visual observation. We concluded, however, that condensation was very likely to have collected on the edge of the floor of the basement in summer, when the relative humidity of the indoor air remained at 90% or higher.

6) The influence of the internal heat generation extended by about 4.0m from the outside wall of the basement in horizontal and vertical directions.

7) Though the ground at the experimental site had identical properties, we confirmed that the fluctuation of the moisture content was dependent on the depth from the ground level. In other words, the fluctuation band of moisture content in the ground was strongly affected by precipitation but only minimally affected by the depth of the underground water table.

Experimental measurements are now underway for a second year to clarify the effects of the initial conditions of the surrounding ground and internal heat generation. In ensuing research we will conduct nonlinear numerical analyses with simultaneous heat and moisture transfer equations to predict the temperature and moisture behavior of the basement and surrounding ground.

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