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SEASONAL HEAT STORAGE IN UNDERGROUND WARM WATER STORES (CONSTRUCTION AND TESTING OF A 500 m^3 STORE)

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Summary

Design, construction and testing of the efficiency of a 500 m^3 warm water pit has been carried through. The aims of the project were:

- gathering practical experience with the actual realization of the pilot plant;
- monitoring of the overall behaviour of the storage system;
- verification and modification of the digital computer program used to simulate the thermal behaviour of the pit.

The store has performed very well. Only minor unforeseen problems developed during installation of the floating "gasket" sealing the top lid at the edges. The results are that good agreement was obtained when comparing the measured thermal behaviour with both the numerical and analytical predicted performances.

1. Introduction

The aim of the project has been to show that warm water pits, uninsulated against the soil, are well suited for seasonal heat storage. The fact that the use of insulation materials are limited to the top surface, will result in a price reduction when comparing with pits built with insulation of the soil interface.

The project contains the following phases:

a. Detailed examination of the soil conditions on the site of the pit.
b. Determination of the thermal properties of the soil using the information from a).
c. Design of the pit using the information from a).
d. Construction of the pit.
e. Simulated operations and measurements.
f. Verification of a digital computer program for simulating the thermal behaviour of the store.
g. Reporting.

The results of phase a), b), and c) have been reported earlier (1).

2. Construction of the store

The pit with a pyramidal geometry was dug into the ground from the ground level. The store/soil interfaces are made waterproof by use of a 2.5 mm polyethylene plastic liner. A photo of the lining work is shown in figure 2, and a cross section is shown in figure 1.

The floating lid is heat insulated by 0.5 m polystyrene and protected against evaporation from the pit and against climatic conditions by use of a 2.5 mm polyethylene plastic bottom liner and a 1.0 mm butyl rubber liner for the topside. The lid was constructed in a "dry dock" next to the pit and was easily floated to the final position. A photo of the final plant is shown in figure 3. The construction was completed in 3 months during the summer of 1982.

The ground water level is 40 m below the ground level.

3. Experimentation

Approximately 80 copper constantan thermocouples are being used to measure temperatures in the water and in the soil under and around the pit. The thermocouples are arranged in chains which are located in two planes as shown in figure 4. The location of the thermocouples in the ground in one of the planes is shown in figure 5.

The temperatures are scanned automatically once an hour. Every day the data logger system prints all the daily mean temperatures on paper and on tape (for later transfer to our computer center).

The heat input to the water in the pit is generated by two gas boilers. The first charge period started in September 1982 with a water temperature of 15°C.

Because of the limited time being available for experimentaion in this project, it was decided to accelerate the testing by reducing the charge/discharge cycle from 365 days to 70 days. Further it was decided to have total temperature mixing of the water in the store. The charge and discharge cycles can be seen in figure 9.

4. Computer model

A computer program has been constructed based on the method of finite differences. The program treats the geometry of 1/8 of the pit and the surrounding soil as indicated in figure 6. The computer code has been constructed to be truly 3-dimensional. The enmeshment is shown in figures 5 and 6. The centre points of the volume elements shown are the meshpoints used in the simulations. The computer program offers the following facilities:

- initial and boundary conditions can be specified freely;
- thermal material properties can be specified separately in every horizontal mesh point plane;
- soil temperatures in mesh points and heat loss from the pit to the soil are calculated at 6-hours time intervals;
- calculated and measured temperatures are linked in the data base to facilitate comparing;
- a yearly simulation cost of about 1.5 CPU minutes on our IBM 3033 computer.

5. Verification of the computer program

The procedure for determining the thermal properties of the soil has been explained earlier (1). The values found were the following:

- coefficient of thermal diffusivity $\alpha = 22\ m^2/yr$
- coefficient of thermal conductivity $\lambda = 1.6\ W/m\ ^oC$
- coefficient of heat accumulation $\sqrt{\lambda\rho c} = 3.0\ kWh/^oC\ m^2\ yr^{1/2}$

Using these findings, measured and calculated temperatures have been compared. As examples the temperatures on the measuring locations 7 and 24 shown in figure 5 are traced in figures 7 and 8. It thus appears that the program can be used in the original form to simulate the thermal behaviour if this type of pit. (No change in soil assumptions was needed).

6. Storage efficiency

Firstly, the storage efficiency in part of the period of testing is investigated. The sum of the accumulated heat loss from the pit to the soil and through the top-lid by conduction is shown in figure 9. (This parameter is part of the output from the computer program). The heat loss during the second discharge period from day 145 to day 180 is used, (the difference between point 2 and 1 in figure 9):

$$\Delta Q_1 = 1.72 \cdot 10^{10} J = 4{,}770\ kWh \qquad (1)$$

(85% is lost to the soil and 15% through the top-lid by conduction)

The heat content of the water in the pit being discharged from 60.6°C to 30°C is (water volume ≃ 540 m^3):

$$\Delta Q_{acc} = 19{,}000\ kWh \qquad (2)$$

The cooling load measured on the discharge ventilator during this period:

$$\Delta Q_{cool} = 12{,}100\ kWh \qquad (3)$$

Consequently heat losses in piping, edge transmission and evaporation losses at the edge of the lid have been:

$$\Delta Q_2 = 19{,}000 - 4{,}770 - 12{,}100 = 2{,}130\ kWh \qquad (4)$$

The major part of ΔQ_2 is an unaccounted loss due to the sealing of the lid at the edges, which has not been included in the computer calculations.

The storage efficiency:

$$\eta = \frac{\Delta Q_{cool}}{\Delta Q_{acc}} = \frac{12{,}100}{19{,}000} = 64\% \qquad (5)$$

Without this unaccounted evaporation loss, the efficiency would have been:

$$\eta \simeq 74\% \qquad (6)$$

Only including the heat loss to the soil, the efficiency will be:

$$\eta' = \frac{19{,}000 - 4{,}770 \cdot 85\%}{19{,}000} = 79\% \qquad (6a)$$

Secondly the thermal behaviour during seasonal performance is investigated. The direct way of using the results of figure 9 goes via the Fourier number.

$$F_o = \alpha \frac{t}{L^2} \quad , \text{ where} \tag{7}$$

α = coefficient of thermal diffusivity, t = characteristic time and L = characteristic lineary dimension of the pit.

In figure 9 the temperature cycle time from day 110 to day 180 is 70 days, which is taken as the characteristic time.

In seasonal operation t = 365 days.

Now using equation (7)

$$\alpha \frac{70 \text{ days}}{L_1^2} = \alpha \frac{365 \text{ days}}{L_2^2} \tag{8}$$

$\Rightarrow$

$$FAK = \frac{L_2}{L_1} = \sqrt{\frac{365}{70}} = 2.283 \tag{9}$$

FAK is the lineary scaling factor which must be applied in order to find a pit which, in seasonal operation, will manifest the efficiencies of equations (5) and (6). The volume is scaled as follows:

$$VOL_{seasonal} = VOL_{70 \text{ days}} \cdot FAK^3 = 6{,}430 \text{ m}^3 \tag{10}$$

To get an estimate of the efficiency in seasonal operation for large pits, the measured efficiencies will be compared to the theoretical efficiencies calculated on the basis of the theory developed by P.N. Hansen (2).

The total heat loss to the soil during a 6-months discharge period in wintertime is given by equation (13) in (2):

$$\Delta Q_{soil} = A \frac{\sqrt{\lambda\rho c}}{\sqrt{\pi}} \left(- \Delta\vartheta \sqrt{1 \text{ year}} + (\vartheta_o - \vartheta_\infty) \left(\frac{\sqrt{\alpha\pi}}{zM} \tfrac{1}{2} \text{ year} + 2\left(\sqrt{t} - \sqrt{t - \tfrac{1}{2}}\right)\right)\right) \tag{11}$$

where

A = the surface area of the store versus the soil
$\sqrt{\lambda\rho c}$ = the coefficient of heat accumulation of the soil
$\Delta\vartheta$ = the temperature amplitude in the store
ϑ_o = the average temperature in the store
ϑ_∞ = the original average temperature of the soil
t = the time in units of years
α = the coefficient of thermal diffusivity of the soil
M = the modulus, which is equal to the ratio volume of store versus surface area of the store
z = a geometry factor

Not accounting for the heat losses through the top lid the efficiency is defined by:

$$\eta' = \frac{\Delta Q_{accumulated} - \Delta Q_{soil}}{\Delta Q_{accumulated}} \tag{12}$$

In the following it is compared if the equation of the theory (11) and (12) will provide an efficiency comparable to equation (6a) for the store of 6,430 m^3 being discharged during seasonal operation.

Using values for the test pit (volume = 540 m^3 and surface area versus the soil = 300 m^2) one gets:

$$A = FAK^2 \cdot 300 = 1564 \text{ m}^2 \tag{13}$$

$$M = \frac{540}{300} \cdot FAK = 4.11 \qquad (14)$$

The geometry factor is given in equation (22) in reference (2) to be z = 2.

Using equation (2) gives:

$$\Delta Q_{accumulated} = FAK^3 \cdot 19{,}000 = 226{,}100 \text{ kWh}$$

Inserting in equation (11):

$$\Delta Q_{soil} = 1564 \frac{3.0}{\sqrt{\pi}} \Bigg(- 15.3^{o}C + (45.3 - 9) \left(\frac{\sqrt{22 \cdot \pi}}{2 \cdot 4.11} 1/2 + 2\left(\sqrt{2} - \sqrt{1\tfrac{1}{2}}\right)\right)\Bigg) \qquad (15)$$

$$\Delta Q_{soil} = 44{,}500 \text{ kWh} \qquad (16)$$

Inserting in equation (12):

$$\eta' = \frac{226{,}100 - 44{,}500}{226{,}100} = 80\% \qquad (17)$$

This result has to be compared with equation (6a).

The agreement is seen to very good and it can be concluded that the analytical expression in equation (11) is fit for predicting heat losses to the soil in pit storage systems.

7. Conclusions

The design and construction of a 500 m^3 warm water pit was carried out with the highest priority being placed on securing accuracy in the testing of the efficiency of the pit during the pilot operations. Thus the details of this design cannot be taken as the technical and economical optimum for future full scale pits.

To simplify the comparison between the measured thermal behaviour of the pit and the numerical and analytical predictions of the performance during the pilot operations, the pit was dug into the ground completely, thus disregarding the normal procedure of securing dirt balance by placing excavated dirt as embankments.

The design and construction procedures have given no reason for changing of future facilities constructed for the same purpose.

The good agreement obtained during the testing between numerical and analytical predictions and measurements seems to indicate that the procedure followed during installation of the measuring points has been satisfactory.

Any future pilot plant and some of the first commercial applications should, perhaps, be equipped with "chains" of thermocouples for temperature monitoring. The chains should be safeguarded against moisture movements in the vertical holes drilled for placing of the measuring chains.

The numerical and analytical predictions of the performance of the pit during operation have been good, and continued observations during the coming year are expected to document the continued decrease in thermal losses predicted by the analytical studies of the operations.

The minor unforeseen difficulties arising during installation of the floating "gasket", which were designed to almost prevent evaporation and excessive heat losses along the joint between the lid and the concrete edge of the pit, are not expected to occur in full scale pits. The reason for this is that the lid on these pits should be fully fastened to the edge of the pit, thus making the warm water, stored in the pit, part of a "closed" system for energy transmission.

References

(1) Hansen, K.K. and Hansen, P.N. Seasonal Heat Storage in Underground Warm Water Stores - Construction and Testing of a 500 m^3 Store. In Solar Energy Applications to Dwellings - Solar Energy R&D in the European Community, Series A, Vol. 2, pp. 404-412. (Ed. W. Palz and C. den Ouden). D. Reidel Publishing Company. 1983.

(2) Hansen, P.N. Analytical Description of the Heat Losses from Underground Thermal Seasonal Heat Stores. Paper presented at the U.S. Department of Energy Conference "Seasonal Thermal Energy Storage", October 19-21, 1981, Seattle, Washington, U.S.A.

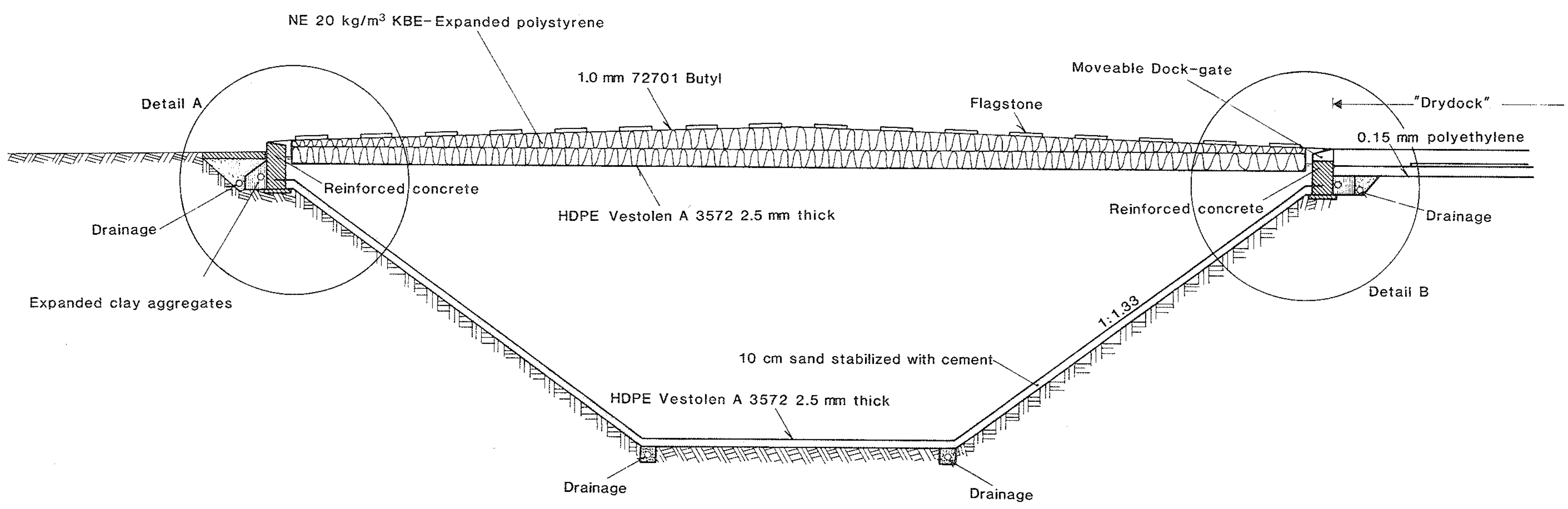

Figure 1. Sectional view of the 500 m^3 test pit.

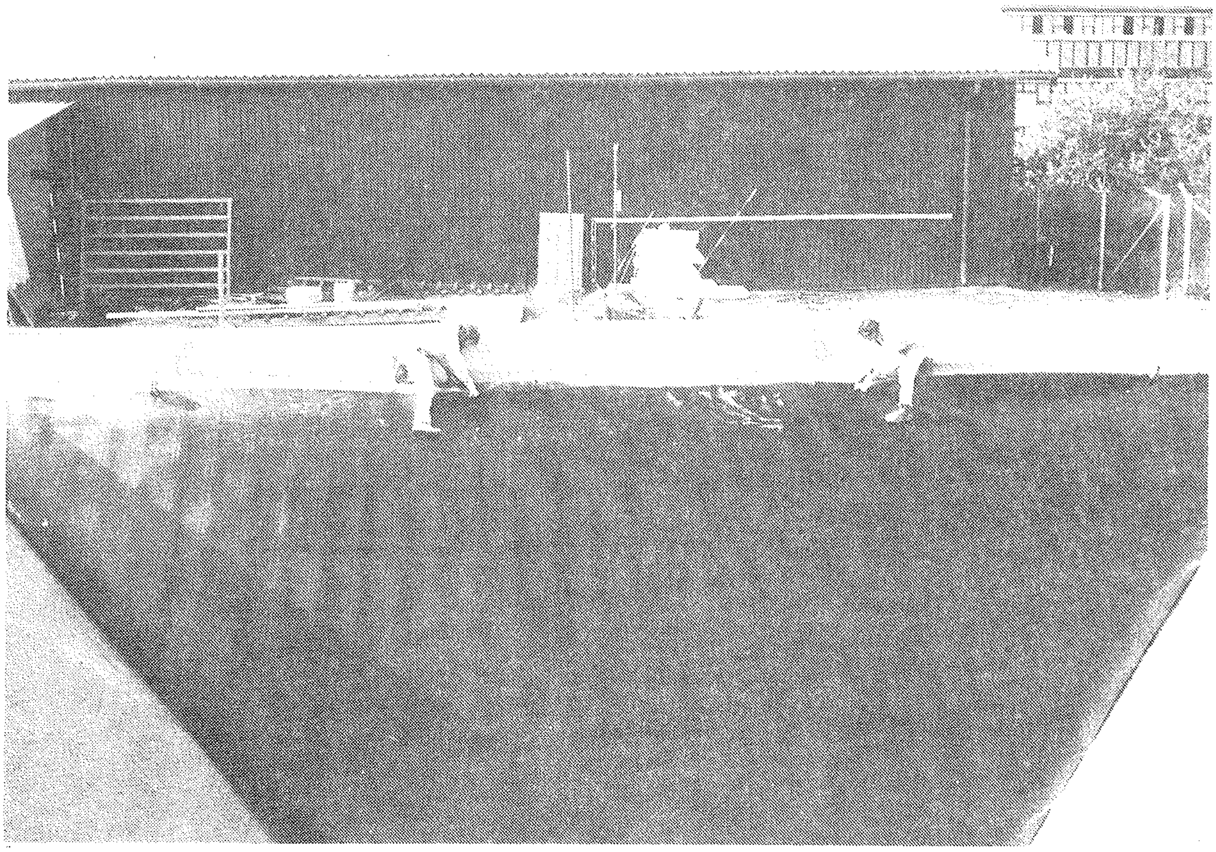

Fig. 2. The lining work in progress.

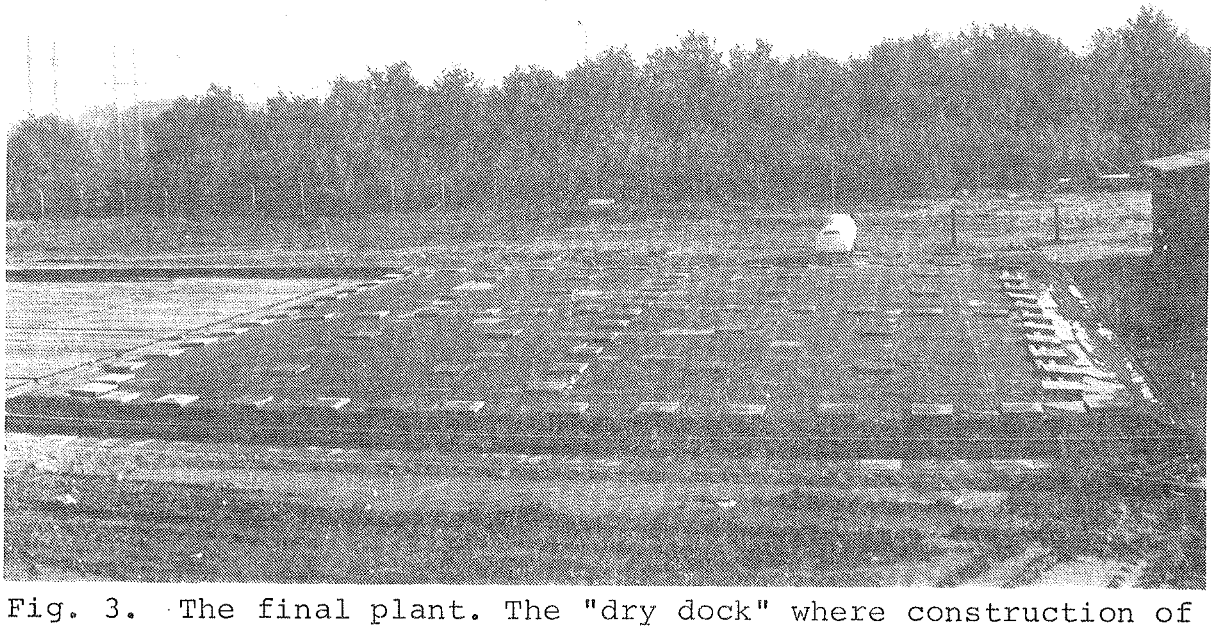

Fig. 3. The final plant. The "dry dock" where construction of the lid was undertaken, is partly seen to the left.

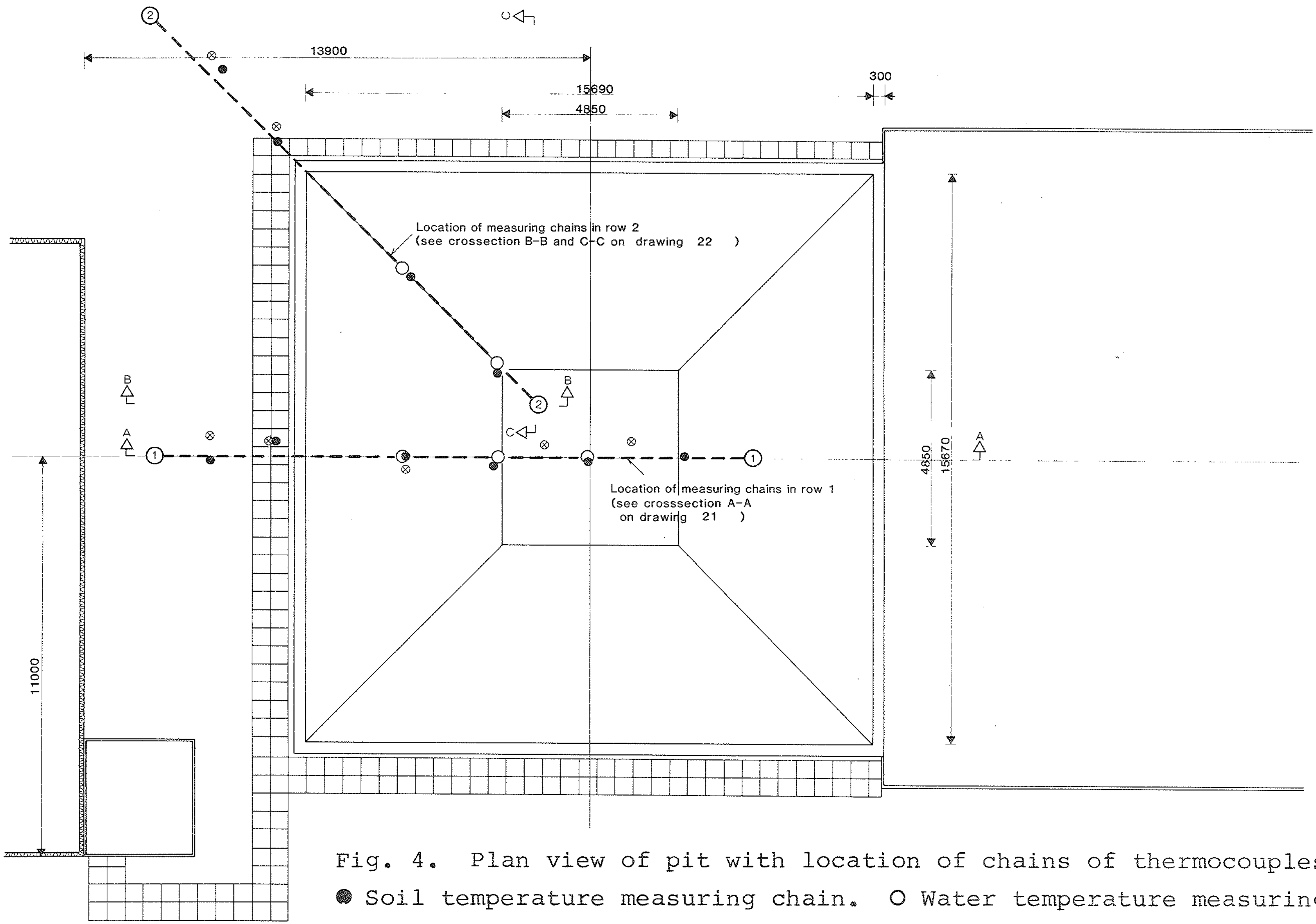

Fig. 4. Plan view of pit with location of chains of thermocouples shown.
● Soil temperature measuring chain. O Water temperature measuring chain.
⊗ Tube for moisture sensor.

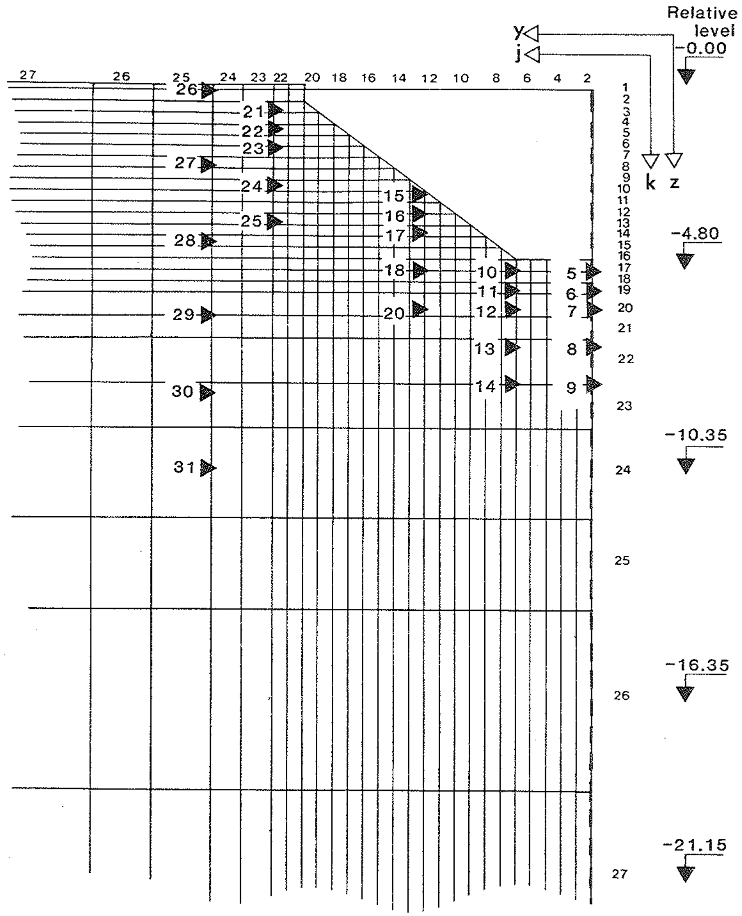

Fig. 5. Enmeshment in a vertical plane.
▶ indicates thermocouple locations.

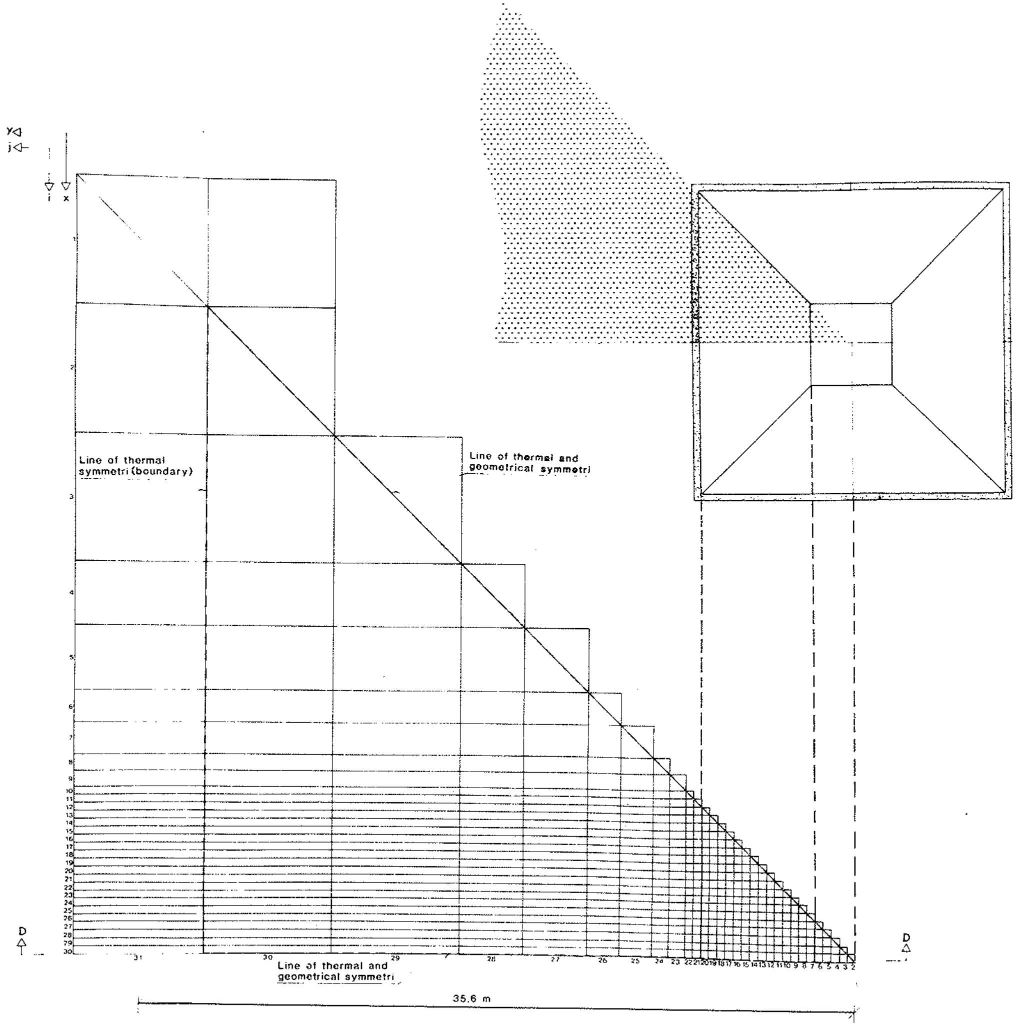

Fig. 6. Enmeshment in a horizontal plane.

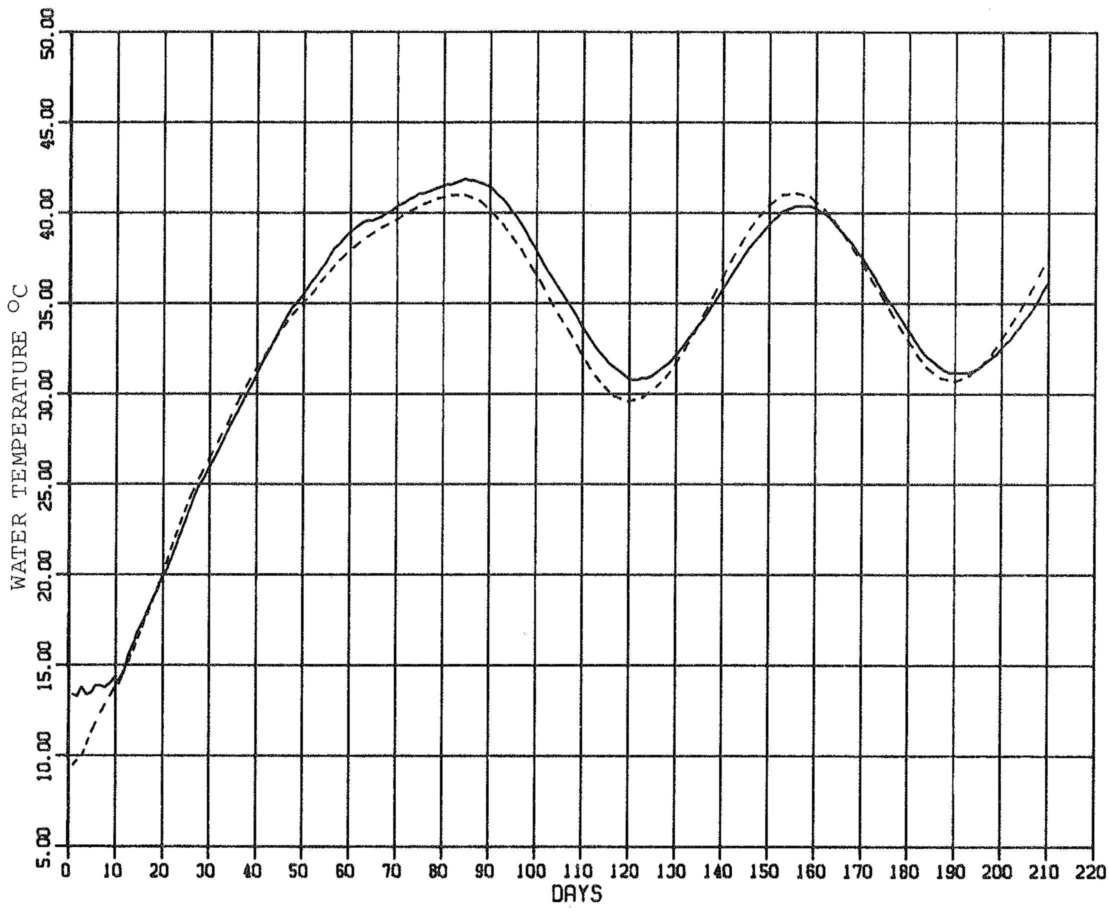

Fig. 7. Measured and calculated temperatures in measuring point location 7 on figure 5.

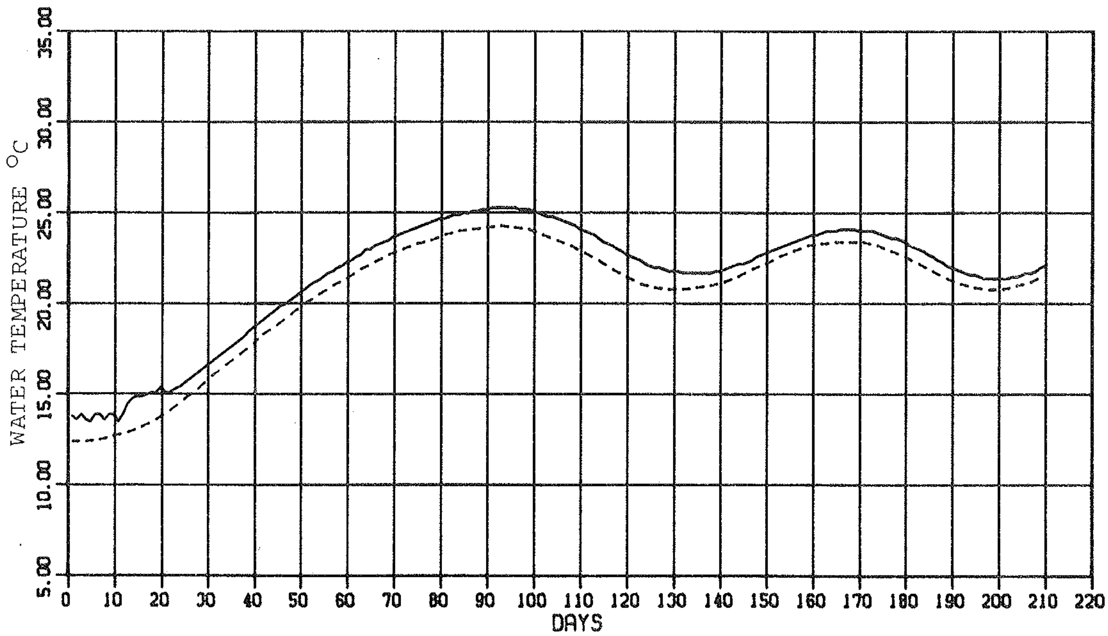

Fig. 8. Measured and calculated temperatures in measuring point location 24 on figure 5.

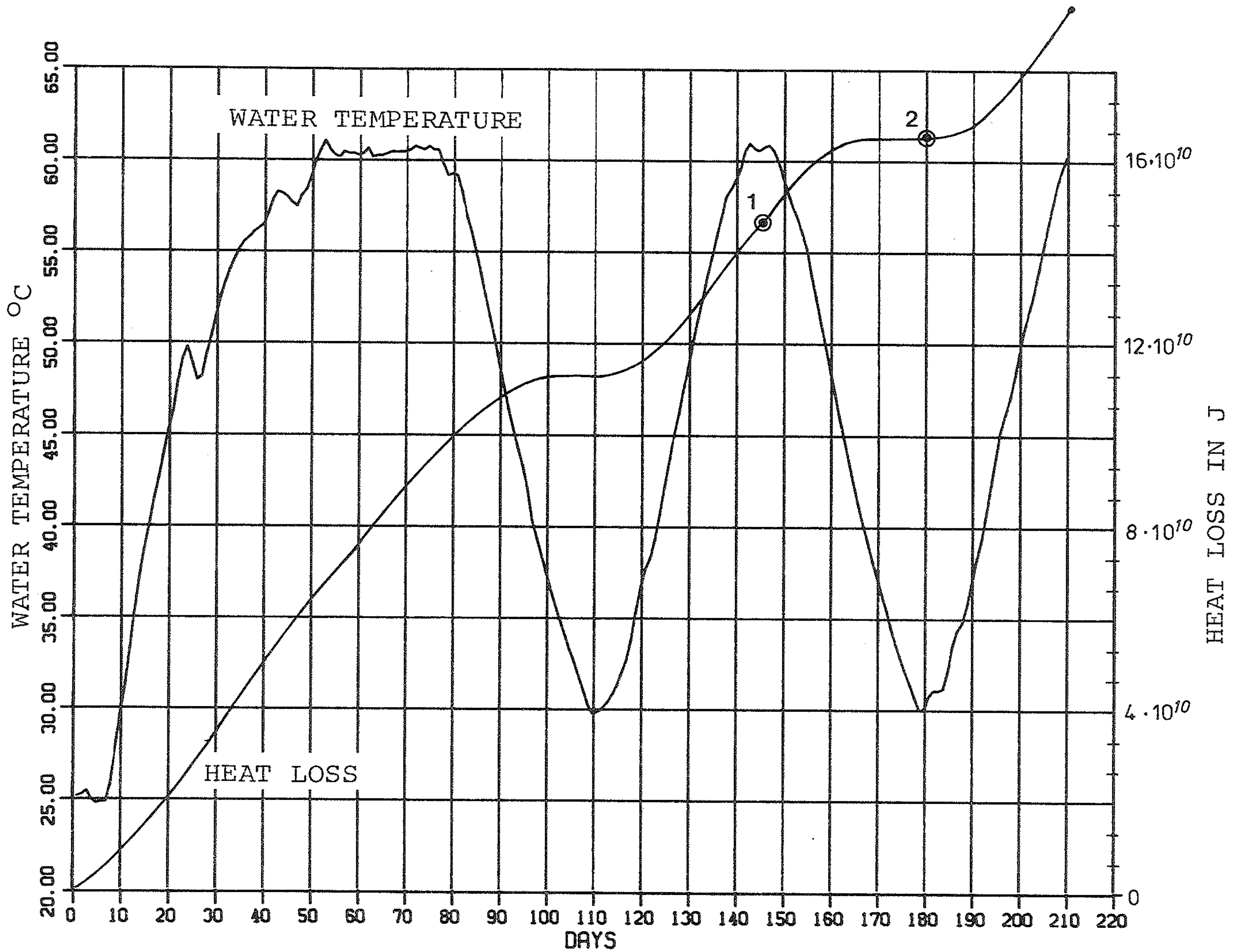

Fig. 9. The measured water temperature in the test pit and the calculated accumulated heat loss from the pit to the soil and through the top lid.