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DEVELOPMENT OF ARTIFICIAL RESERVOIRS BY INDUCING LAND SUBSIDENCE

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Abstract

In the project Lago de Texcoco four lakes are being built using pumping of groundwater to produce land subsidence. Mexico City as well as neighbouring Texcoco Lake subsoils, constitute leaky aquifer systems. Groundwater hydrology can be used to predict ground settlements and therefore to plan and control the corresponding works. In this paper the studies that in this manner have been carried out at Texcoco, Mexico, are briefly described.

Introduction

In the Proyecto Texcoco (1969) two lakes are being built in the first stage of its development and two more will be built in the second one. To construct them groundwater is being pumped in order to produce land subsidence 8m deep. Mexico City as well as neighbouring Texcoco Lake subsoil constitute leaky aquifer systems, and surface settlements are sensibly equal to the volume of extracted water. Thus, well hydraulics has been used to predict land subsidence.

The studies carried out in the period 1973-75 covered two aspects: the applicability of leaky aquifer theories; and the settlement analysis for the "Proyecto Texcoco". The applicability of the theories, as it is presently understood, was the subject of a previous report (Herrera, 1974). This paper describes the second part of the study (Herrera et al, 1974) in which many data and observations gathered in previous work (Proyecto Texcoco, 1969) were used. The main purpose of the analysis was to determine the feasibility of the project and to detect unforeseen problems that could endanger its successful completion. The description given here will be restricted to one of the lakes, called Texcoco Sur.

Relations between soil mechanics and well hydraulics

Well hydraulics is from the point of view of soil mechanics a consolidation problem. Some relations between the notations used in both of these sciences is given in this section (Terzaghi, 1956; Walton, 1970).

Consolidation coefficient C_v and permeability K, are related by:

$$K = C_v M_v \gamma_w \tag{1}$$

where γ_w is the specific weight of water and M_v the compressibility index. On the other hand:

$$C_v = \alpha = \frac{K}{S_s} = \frac{T}{S} \tag{2}$$

Here, S_s and S are the specific and total storage coefficients, respectively, and T is the transmissivity. Consider two aquifer separated by an aquitard of thickness b'; then, the pumping time t required for the interaction between the aquifers to be perceptible satisfies (Herrera, 1974):

$$\alpha' t/b'^2 = T_u/4 = t_u H^2/4C_v = \frac{1}{6} \tag{3}$$

Here, 2H=b', t_u is the time required to achieve a u^0/o degree of consolida-

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tion under conditions of unidimensional flow, T_u is Terzaghi's time factor and the primes refer to aquitard properties.

Description of the study

To test the method of construction an experimental field was pumped for a period of 10 months (October, 1967 through July, 1968) (Proyecto Texcoco, 1969). In this place many soundings were made, particularly three deep soundings (Marsal, 1969). In order to verify the stratigraphy, a standard penetration test at a depth of 60m, was carried out. The mechanical properties of the aquifers were determined by means of several pumping tests. The piezometric heads were registered during the entire 10 months pumping period. Later, similar soundings and tests were made at the actual area of construction, before pumping was started.

A hydraulic model was developed for the experimental field which was calibrated using the measurements taken during its pumping. This model was later adjusted on the basis of Texcoco Lake conditions. Settlement predictions for this site were made under design, as well as actual operation conditions.

The hydraulic model

The field and laboratory observations imply in view of the range of applicability of the theories (Herrera, 1974), the following hydraulic model for the experimental field:

a) The subsoil constitutes a leaky aquifer system (fig 1), which has two main aquifers: the upper one called "hard layer" and the lower one called "deep deposits". The hard layer is limited above and below by aquitards called the upper and lower clay formations respectively; the deep deposits are limited below by an impervious stratum. All the layers are homogeneous.

b) The flow is vertical in the aquitards.

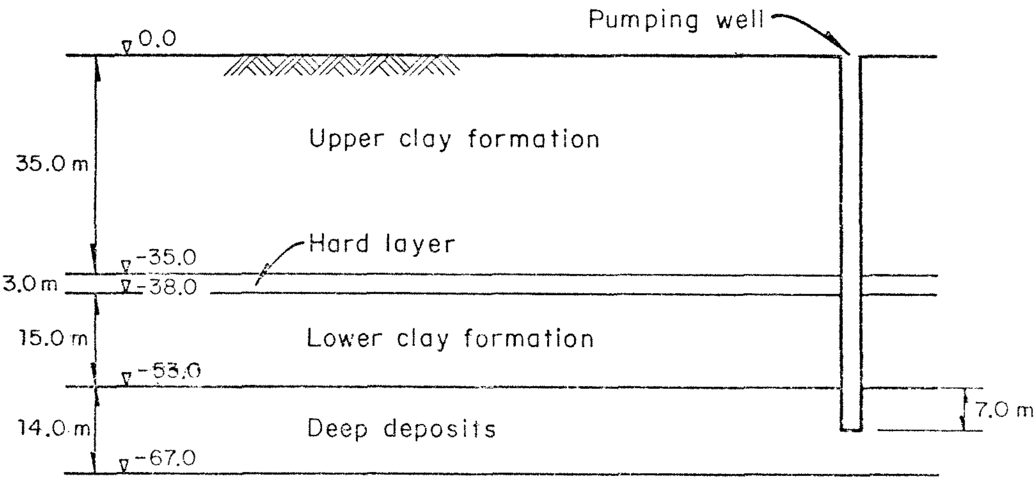

Fig. 1 Stratigraphy of the experimental field.

TABLE 1. PROPERTIES AT THE EXPERIMENTAL FIELD

Stratum	Thickess, b, in m	Permeability, K, in m/day	Transmissivity, T, in m^2/day	Storage Coefficient, S	$C_v=\nu=T/S$, in m^2/day	Specific storage Coefficent, S_s, in m^{-1}
Upper Clay	$b' = 35$ (1)	$K' = 0.47 \times 10^{-3}$	$T' = 1.64 \times 10^{-2}$	$S' = 1.82$	$C_v' = 9 \times 10^{-3}$ (1)	$S' = 5.2 \times 10^{-2}$
Hard Stratum	$b_1 = 3$	$K_1 = 6$ (1)	$T_1 = 18$	$S_1=1.65 \times 10^{-4}$	$C_{v_1}=1.08 \times 10^{+5}$	$S_{s_1}=5.5 \times 10^{-5}$ (1)
		$K_1 = 8$ (2)	$T_1 = 24$ (2)	$S_1=2.65 \times 10^{-4}$ (2)	$C_{v_1}=9.05 \times 10^{+4}$ (2)	$S_{s_1}=8.83 \times 10^{-5}$ (2)
Lower Clay	$b' = 15$	$K'' = 1.44 \times 10^{-5}$ (1)	$T'' = 2.16 \times 10^{-4}$	$S'' = 0.24$	$C_v'' = 9 \times 10^{-4}$ (1)	$S_s'' = 1.6 \times 10^{-2}$
Deep Deposits	$b_2 = 7$ (1)	$K_2 = 7.8$ (1)	$T_2 = 42$	$S_2=3.85 \times 10^{-4}$	$C_{v_2}=1.08 \times 10^{+5}$	$S_{s_2} = 5.5 \times 10^{-5}$ (1)
	$b_2 = 14$ (2)	$K_2 = 7.5$ (2)	$T_2 = 105$ (2)	$S_2=1.24 \times 10^{-3}$ (2)	$C_{v_2}=8.47 \times 10^{+4}$ (2)	$S_{s_2} = 8.83 \times 10^{-5}$ (2)

(1) Herrera et al, 1974

(2) Values yielded by calibration

c) There is no significant interaction between the main aquifers; thus, they work independently.

d) Each of the main aquifers is governed by the theory for small values of time (Herrera, 1974).

e) The strata are unlimited in the horizontal directions.

f) The volume of the lake created, is sensibly equal to the water extracted from the formations.

Table 1 gives the dimensions and properties of the strata at the experimental field. To apply this model to Texcoco Sur it was necessary to make the changes implied by table 2. An important change in the

TABLE 2. PROPERTIES AT TEXCOCO SUR

Stratum	Thickess, b_1, in m	Permeability, K, in m/day	Transmissivity, T_1, in m^2/day	Storage Coefficients, S	Coefficent C_v, in m^2/day	Specific storage Coefficient, S_s, in m^{-1}
Upper Clay	32	0.47×10^{-3}	1.5×10^{-2}	1.66	9×10^{-3}	5.2×10^{-2}
Hard Stratum	2	8	16	1.77×10^{-4}	$9 \times 10^{+4}$	8.8×10^{-5}
Lower Clay	16.5	1.44×10^{-5}	2.38×10^{-4}	0.26	9×10^{-4}	1.6×10^{-2}
Deep Deposits	8.5 or infinity	7.5	63	7.33×10^{-4}	$8.5 \times 10^{+4}$	0.9×10^{-4}

stratigraphy is that horizontal variations were too big to be ignored (fig 2).

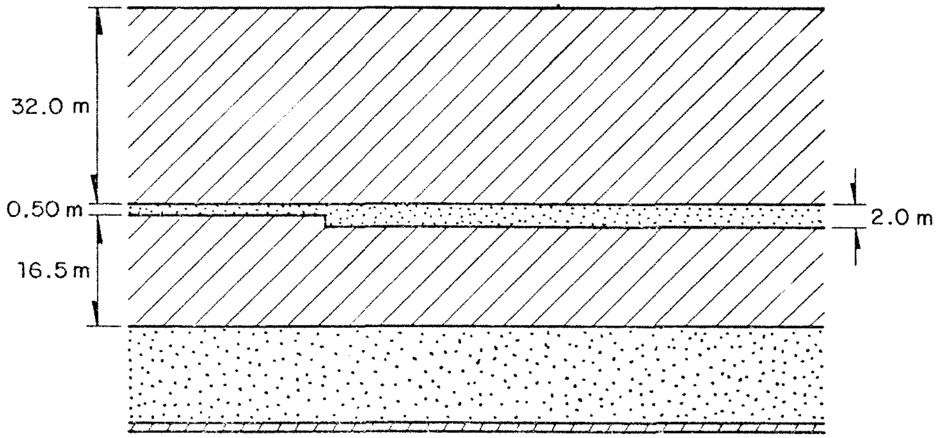

Fig. 2 Stratigraphy of Texcoco Sur Lake.
Measures, in meters.

Calibration of the model

The knowledge of the range of applicability of the theories, permitted to obtain reliable results and to keep the possible error sources under effective control. It was then possible to explain observed discrepancies and make adjustments in the model to remove them (Herrera et al, 1974). The basis for the calibration was comparison of calculated drawdowns and ground settlements with those observed (fig 3).

The drawdown observations used as basis for the comparison were taken at piezometric station EP1, which worked normally during the ten month period. The details of the computations are given by Herrera et al (1974).

The pumping period was divided in the manner shown in table 3. Satisfactory agreement was found between observed and computed piezometric heads when the property values shown in table 1 were used and a discharge distribution of 18% at the hard layer and 82% at the deep deposits was assumed. Many wells were closed on December 1968 which apparently produced a discharge redistribution; after this date 20% of the discharge came from the hard layer and 80% from the deep deposits.

After the model had been calibrated on the basis of drawdowns, overall comparison of the predicted and observed land settlements was made. The observations consisted of levelings of the area, carried out at several dates during the pumping period. For a pumping period as long as the one preformed at the experimental field, it was found that an important proportion of the water extracted, comes from points outside the area of interest and which were not covered by the levelings. Restricting the predictions to the area of interes, table 4 was obtained.

To simplify the computations, the total extraction was assumed to occur at the geometrical center of the field.

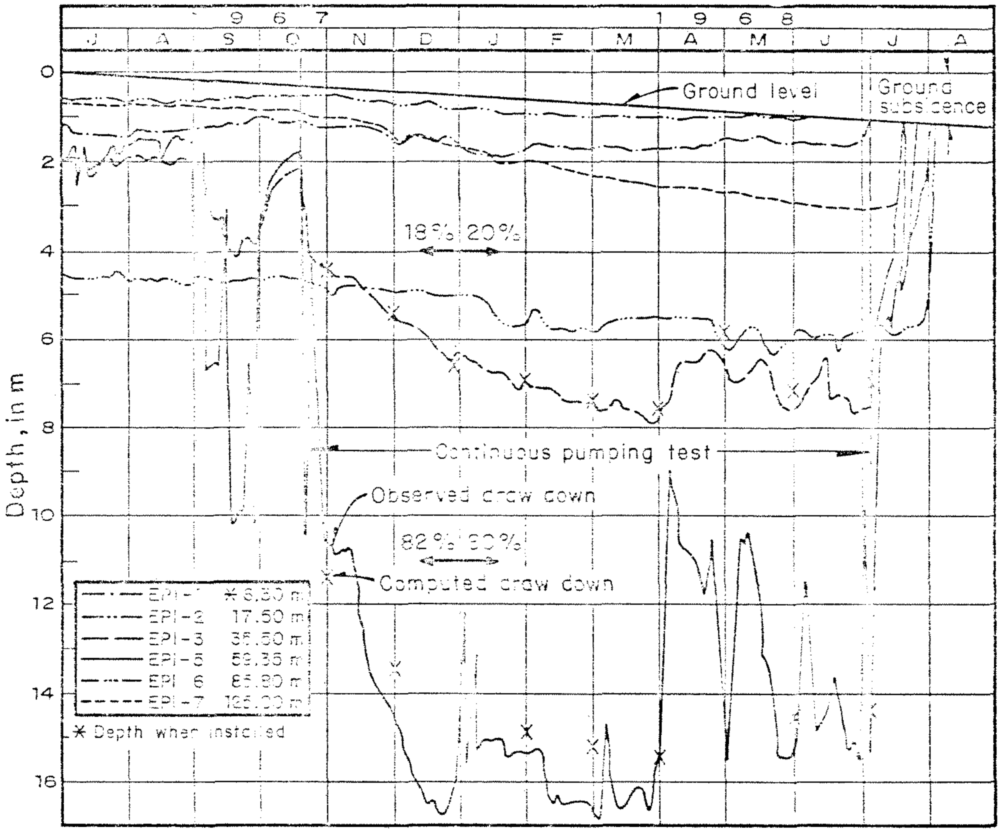

Fig. 3 Observed and computed drawdowns at EP1 station.

TABLE 3. PUMPING PERIODS

Period	Starting date			Final date			Duration in days	Days Accumulated
	Day	Month	Year	Day	Month	Year		
1	21	October	1967	30	November	1967	41	41
2	1	December	1967	28	December	1967	28	69
3	29	December	1967	31	January	1968	34	103
4	1	February	1968	29	February	1968	29	132
5	1	March	1968	31	March	1968	31	163
6	1	April	1968	30	April	1968	30	193
7	1	May	1968	31	May	1968	31	224
8	1	June	1968	4	July	1968	34	258

TABLE 4. PREDICTED Vs OBSERVED EFFICIENCY

Days	Efficiency (%)	
	Computed	Observed
69	24.8	28.0
150	21.1	26.5
224	20.5	14.0
270	19.4	--
1 800	13.0	--

Therefore, the actual efficiency has to be smaller than the one predicted, because many wells are closer to the field limits than its geometrical center.

Application to Texcoco Sur

When the calibration of the model was finished one of the main limitations of the project was a possible drastic reduction of the efficiency, which could render impossible to obtain the foreseen discharges. For the pumping period of the project (5 to 8 years), the maximum admissible drawdowns can be insufficient to yield the required discharges. On the other hand, at first it was thought that probably a large proportion of the land subsidence in Texcoco Sur was to occur outside the area of interest, because the envisioned pumping period is much larger than for the experimental field. However, due to the much larger dimensions of Texcoco Sur it was found that is not the case.

When computing the land settlements at Texcoco Sur, it was necessary to keep the head constant at some wells instead of imposing the more usual condition of constant discharge. This was due to the fact that the limiting drawdown values were reached. Also, because some stratigraphic features were not sufficiently clear, it was feared that the deep deposits could have a thickness practically unlimited in some area (fig 4); however, observations made once the pumping was started proved this suspicion to be false. The details of the computations are given in reference (Herrera et al., 1974).

Conclusions and recommendations

The main conclusions and recommendations were as follows:

i) The adopted hydraulic model was satisfactory to describe the land settlements on sections 1, 2 and 3 (fig 4).

ii) At sections 4 and 5 there are unforeseen soil formations which apparently consist of thin pervious strata which lie in the lower clay formation. These formations do not endanger the success of the project, because they considerably increase the speed of land subsidence and the pumping efficiency.

iii) It will be possible to achieve volume of soil settlements required for the project completion.

iv) To avoid important differential settlements, it was

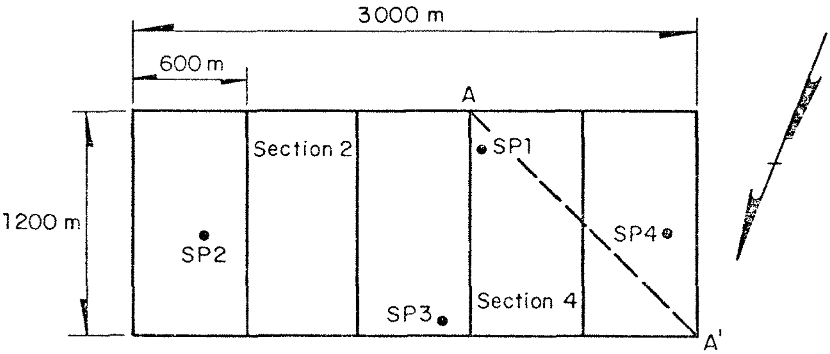

Fig. 4 Lago de Texcoco Sur. Dotted line limits area where thickness of deep deposits apparently was unlimited.

recommended to extract three times as much water from section 2 than from section 4.

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