FIFTH AUSTRALASIAN CONFERENCE
on
HYDRAULICS AND FLUID MECHANICS
at
University of Canterbury, Christchurch, New Zealand
1974 December 9 to December 13

OPTIMAL DESIGN OF WATER WELLS IN UNCONSOLIDATED SEDIMENTS

by

C.R. Dudgeon[1] and M.H. Keshavarz[2]

SUMMARY

Optimal design of wells in unconsolidated sediments requires information on the drawdown-discharge relationship for the range of practical designs and hydraulic characteristics of aquifer materials met in the field. Well diameter, degree of penetration, screen length, type of screen and the presence or absence of a gravel pack all influence the drawdown-discharge relationship.

A research program funded by the Australian Water Resources Council has led to the development of finite element computer programs which allow the drawdown-discharge relationship and other factors such as the variation of approach velocity at the well boundary to be predicted for a more comprehensive range of conditions than it has been possible to treat in the past.

In the work described in this paper the hydraulic information has been combined with cost data to determine the design of a well which would produce water at minimum cost to irrigate a farm of between 50 and 75 acres at a site in Southern Queensland, Australia. The particular case was chosen because the aquifer material was such that non-Darcy flow would occur near the well at the required discharge.

1. Senior Lecturer in Civil Engineering, Water Research Laboratory, School of Civil Engineering, University of New South Wales.

2. Research Student, Water Research Laboratory, School of Civil Engineering, University of New South Wales.

1. Introduction

Selection of the optimal design for a water well in unconsolidated sediments involves the choice of well diameter, degree of penetration, screen length and position and type of pump. Analysis of the cost of water for alternative practical designs calls for a knowledge of the drawdown-discharge relationship for each case since the cost of pumping depends on the water level in the well. The relationship depends on the hydraulic characteristics of the aquifer material surrounding the well and the aquifer and well geometries. The properties of the aquifer material close to the well have a greater influence on the drawdown than those of more distant material, particularly in cases where non-Darcy flow develops near the well at high flow rates. Natural inhomogeneity, gravel packing and drilling and development techniques may cause radial variations in the hydraulic characteristics. When these variations are considered with the wide range of possible well geometries and aquifer types it is clear that the analysis of many complex flow cases may arise in the design of wells.

In the past, analytical predictions of the drawdown-discharge relationship have been restricted to those cases involving simple geometry and Darcy flow. Electrical analogues have been used to analyse more complex Darcy flow problems and a few attempts have been made to extend these to non-Darcy flow.

A research program funded by the Australian Water Resources Council has led to the development of finite element computer programs which allow the drawdown discharge relationship and other pertinent information such as the distribution of entrance velocity along the screen to be predicted for a more comprehensive range of conditions than it has been possible to treat in the past.

The purpose of this paper is to draw attention to the availability of the computer programs and give an example of their use in the design of a well in a particular location. In the work described the hydraulic information was combined with cost data to determine the design of well which would produce water at minimum cost to irrigate a farm of between 50 and 75 acres (20-30 ha) at a site in Southern Queensland, Australia. This site was used for field testing during the course of the Australian Water Resources Council research project so the hydraulic characteristics of the aquifer material in which the well would be constructed were known in advance. The particular case was chosen because the aquifer material was such that non-Darcy flow would occur near the well at the required discharge.

It should be noted that in this paper the term "well" is used to refer to any cylindrical vertical hole used to extract water from an aquifer, regardless of diameter. It encompasses the terms "bore" and "borehole" commonly used to describe wells of small to medium diameter constructed by rotary or cable tool drilling methods.

2. The Design Problem

2.1 The General Case

The general problem is to select a well design which, for the particular location, satisfies the discharge and economic criteria. In the example chosen in this paper the criterion chosen was to minimise the cost of water at the well head for a limited range of discharge. Under other circumstances it might be necessary to minimise the cost of water without specifying the discharge or to adopt some other criterion. Only in the case of maximising the discharge regardless of cost can it be assumed that the well with the greatest specific capacity (discharge per unit drawdown) is the optimum case. In all other cases cost factors must be combined with the hydraulic information obtained by analysing the flow towards and into the well to select the best design.

2.2 The Example Given

(a) Pumping Rate. The required pumping rate for the problem described was based on supplying 3 feet (0.9m) of water over a period of 3 irrigation seasons with a total of 3,000 hours of pumping. The total quantity to be pumped was 150 acre feet ($185 \times 10^3 m^3$) for a 50 acre (20 ha) farm and 225 acre feet ($277 \times 10^3 m^3$) for a 75 acre (30 ha) farm. These were set as the minimum and maximum farm sizes to be considered.

(b) Aquifer Properties. Determination of the in-situ hydraulic characteristics of the aquifer material near the well and the average characteristics of the aquifer as a whole requires pump testing of a trial well. This had been done. The results, together with information obtained by drilling and geological survey, led in this case to the use of the following data in the numerical model.

Aquifer type - confined, single
Aquifer thickness - 10 feet (3.0m)
Radius of influence - 1,000 feet (305 m)
Standing water level - 10 feet (3.0m) below ground surface
Available drawdown - 30 feet (9.1m)
Aquifer material - D_{85} = 29 mm, D_{60} = 15 mm
D_{50} = 10 mm, D_{40} = 6mm
D_{15} = 0.6 mm, D_{10} = 0.3 mm

hydraulic conductivity = 0.3 ft/min (0.0015 m/s)

Darcy flow limit = 0.03 ft/min (0.00015 m/s)

Forcheimer coefficients for non-Darcy flow: a=3.0 min/ft., (590 s/m), b = 10.0 $(\text{min/ft})^2$ $(388\text{x}10^3\ \text{s}^2/\text{m}^2)$

(c) The Range of Practical Designs. For an aquifer of this thickness and depth, well diameter between 6 inches (0.15m) and 48 inches (1.22 m) were considered practical. The larger diameter holes could be constructed by the bucket auger method.

Normal commercial stainless steel wire wound screens or slotted casing were considered for use. Gravel packing was found to be inappropriate when the normal criteria for the size of material required for a gravel pack were examined in the light of the rather coarse non-uniform material of the aquifer. The screen lengths and positions considered were those shown in Figure 1 plus those for 40%, 60% and fully penetrating fully screened wells.

(d) Application of Computer Programs. The computer program to be used to analyse a particular case should be chosen to minimise the computing time.

For fully penetrating and fully screened wells a one-dimensional program for axi-symmetric flow was used. For fully penetrating but partially screened wells and partially penetrating wells it was necessary to use a two-dimensional axi-symmetric program to allow for the pronounced convergence of streamlines in a vertical plane near the well.

A range of drawdowns in 5 feet (1.5m) intervals between 5 feet (1.5m) and 30 feet (9.1m) was used when computing drawdown-discharge curves for the alternative well designs. The two-dimensional program requires drawdown to be specified and discharge calculated while for the one-dimensional program either variable can be specified. For uniformity in the treatment, drawdown was specified in all cases. Additional development of the two-dimensional program to allow discharge to be specified would be warranted if many problems of this type were to be solved. Given a specific discharge, the trials to determine the drawdowns for specific designs could then be performed in the computer.

(e) Drawdown-Discharge Curves. Typical drawdown-discharge curves are shown in Figures 2 and 3 for 6 inch (0.15m) and 24 inch (0.61m) diameter wells and various degrees of penetration and screen configurations.

(f) Entrance Velocities. Assuming that about half the open area of the screen would be blocked by aquifer material and taking the open area of commercial screen and saw cut perforated casing to be 55% and 10% of the peripheral surface respectively, actual open areas of 28% and 5% were adopted for calculating entrance velocities. To prevent sand pumping and excessive screen blockage an upper limit of 10 feet per minute (0.05 m/s) was placed on entrance velocity for acceptable designs.

(g) Cost Analysis. Those designs which would produce the required amount of water and satisfy the entrance velocity requirement were subjected to cost analysis.

Construction costs were subdivided into an establishment charge and the costs of drilling and casing, screen and fittings and development. Pumping costs were determined from the capital cost of the pump and installation and power charges. It should be noted that in this example the depth of the aquifer was such that it was feasible to locate a normal centrifugal pump on a platform above the standing water level for large diameter wells. The cost of such a pump is significantly lower than that of a comparable submersible pump.

The total cost of water made up of capital and operating costs was calculated for each of the hydraulically acceptable designs. Construction costs, interest rates, power charges and lives of well components were selected after discussions with Australian well constructing authorities. The rates vary from time to time and place to place and must be decided prior to the design of a well in any given location.

Table 1 shows the minimum cost of water determined for each well diameter considered for the supply of 150 acre feet ($185 \times 10^3 m^3$). The minimum of \$2.90 per acre foot (\$2.36 per $10^3 m^3$) was found to occur for the 30 inch (0.76m) diameter well. However, similar figures for the supply of 225 acre feet ($277 \times 10^3 m^3$) show that a lower minimum of \$2.80 per acre foot (\$2.28 per $10^3 m^3$) occurs for the maximum practical diameter of 48 inches (1.22m). Both minima occurred for a fully screened fully penetrating well with a drawdown of 25 feet (7.6m).

Table 1

Well Diameter		Total Cost of pumping	Cost per	
inches	m		acre-foot	$10^3 m^3$
6	0.15	\$544.08	\$3.63	\$2.95
8	0.20	\$474.57	\$3.17	\$2.58
10	0.25	\$492.37	\$3.28	\$2.67
12	0.30	\$494.35	\$3.30	\$2.69
16	0.41	\$510.27	\$3.40	\$2.77
20	0.51	\$514.85	\$3.44	\$2.80
24	0.61	\$550.30	\$3.67	\$2.98
30	0.76	\$435.59	\$2.90	\$2.36
48	1.22	\$477.76	\$3.18	\$2.59

3. Discussion and Conclusions

In the example, large diameter wells were found to produce water at a lower cost than small diameter wells. This is the result of being able to construct large diameter holes into the shallow aquifer and locate a normal centrifugal pump within the hole for all but the maximum drawdown considered.

No attempt was made in this work to allow the computer to automatically select the optimal design. The results were obtained by scanning the printout of the computations and manually calculating the costs of the likely alternatives. Any more complex set of constraints would call for further programming to eliminate the tedium of making the comparisons. At present, for the simple conditions stipulated, the procedures are being further developed to allow the calculations to be performed on a remote typewriter terminal.

Acknowledgements. Grateful acknowledgement is given to Pongsarl Huyakorn, who developed the finite element programs, for assistance with the application of the programs in this investigation.

References

1. Dudgeon, C.R. et al "Hydraulics of flow near wells in unconsolidated sediments", University of New South Wales, Water Research Laboratory Report No. 126, Vol. 2, March 1973.

2. Huyakorn, P.S. "Computer programs for solving two-regime flow towards wells", Supplementary volume of Ph.D. thesis entitled "Finite element solution of two-regime flow toward wells", University of New South Wales, 1974.

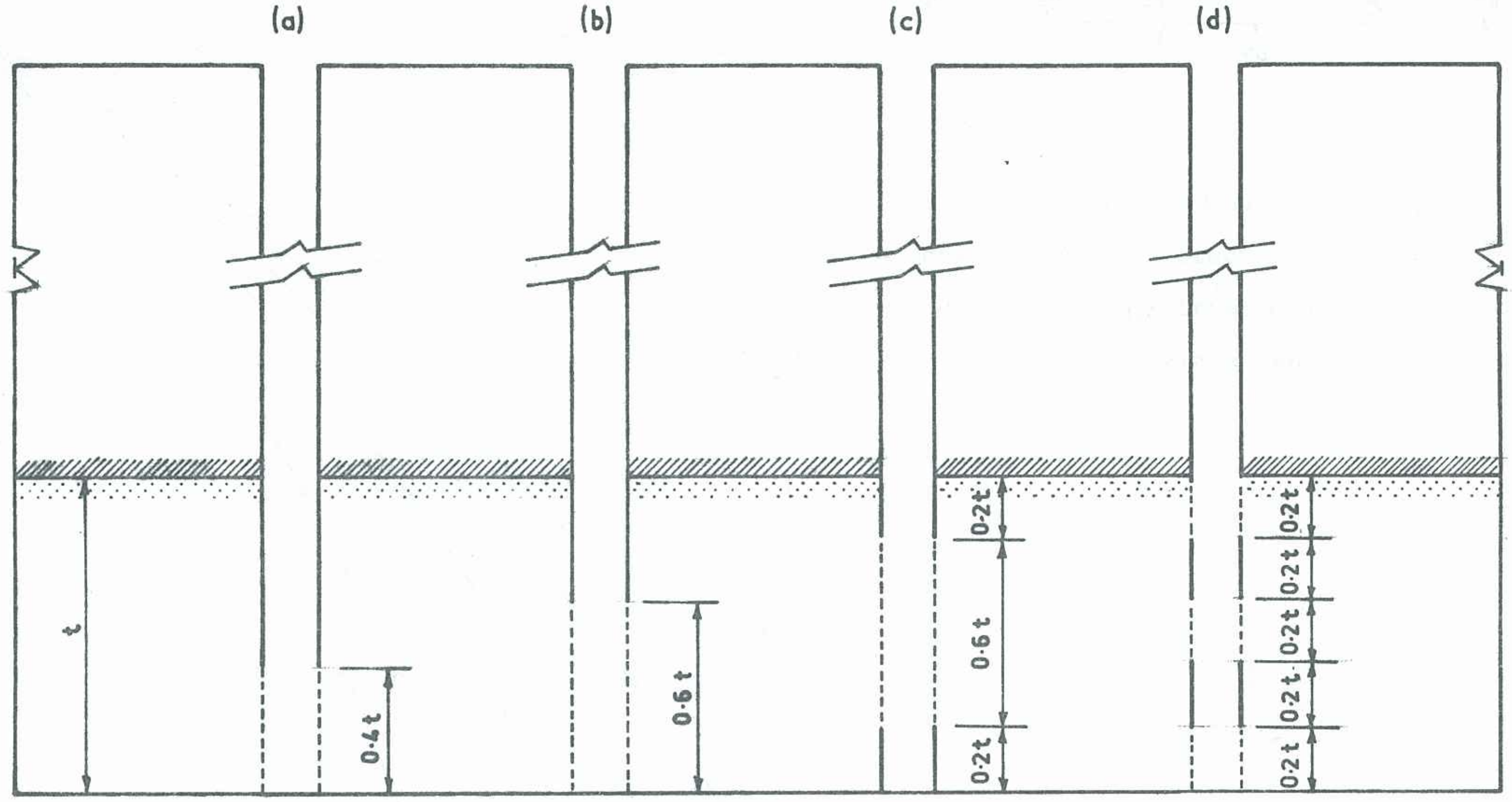

FIGURE 1: SCREEN LENGTHS AND POSITIONS FOR ALTERNATIVE DESIGNS.

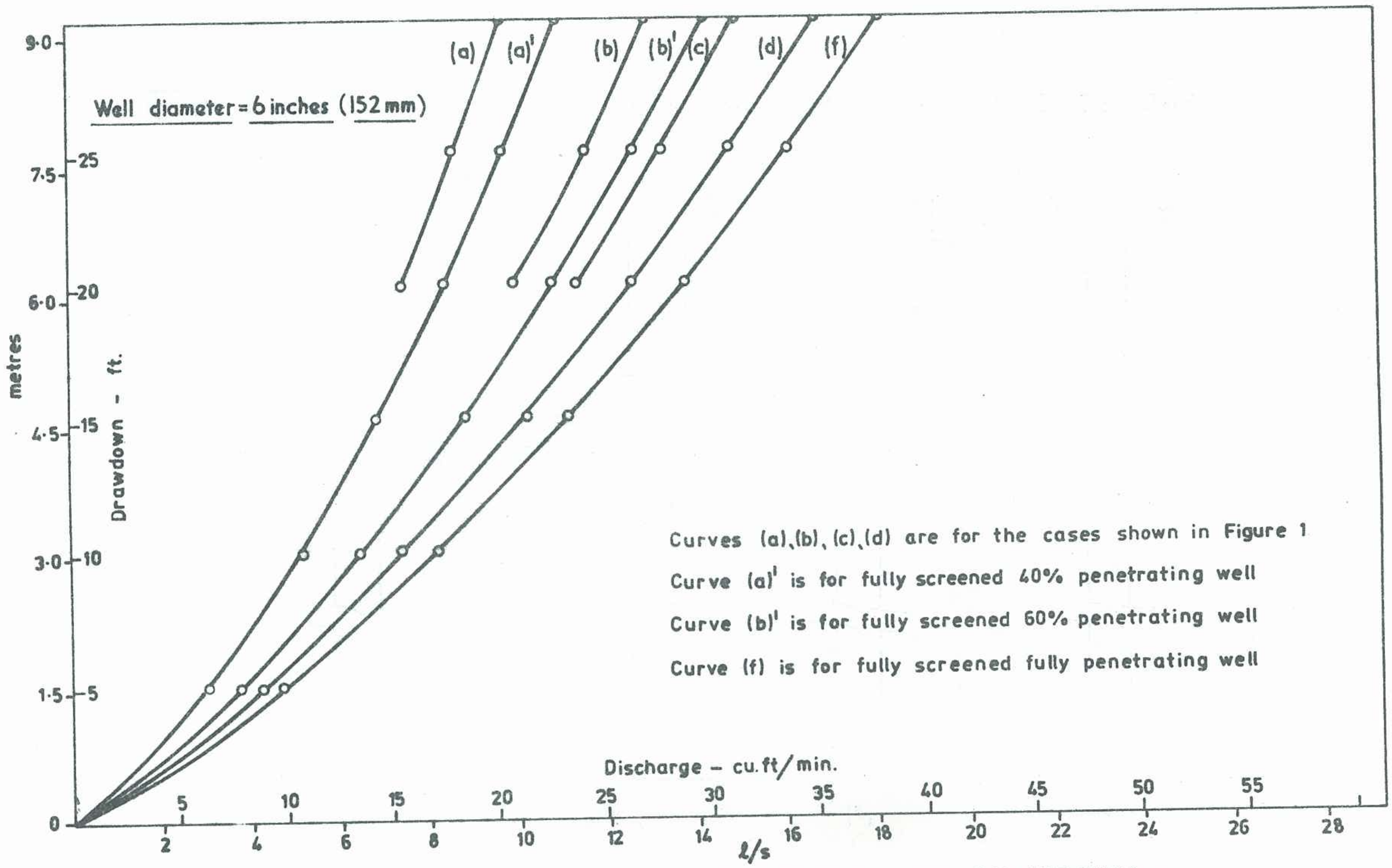

FIGURE 2: EFFECT OF SCREEN LENGTH AND POSITION ON DRAWDOWN - DISCHARGE RELATIONSHIP

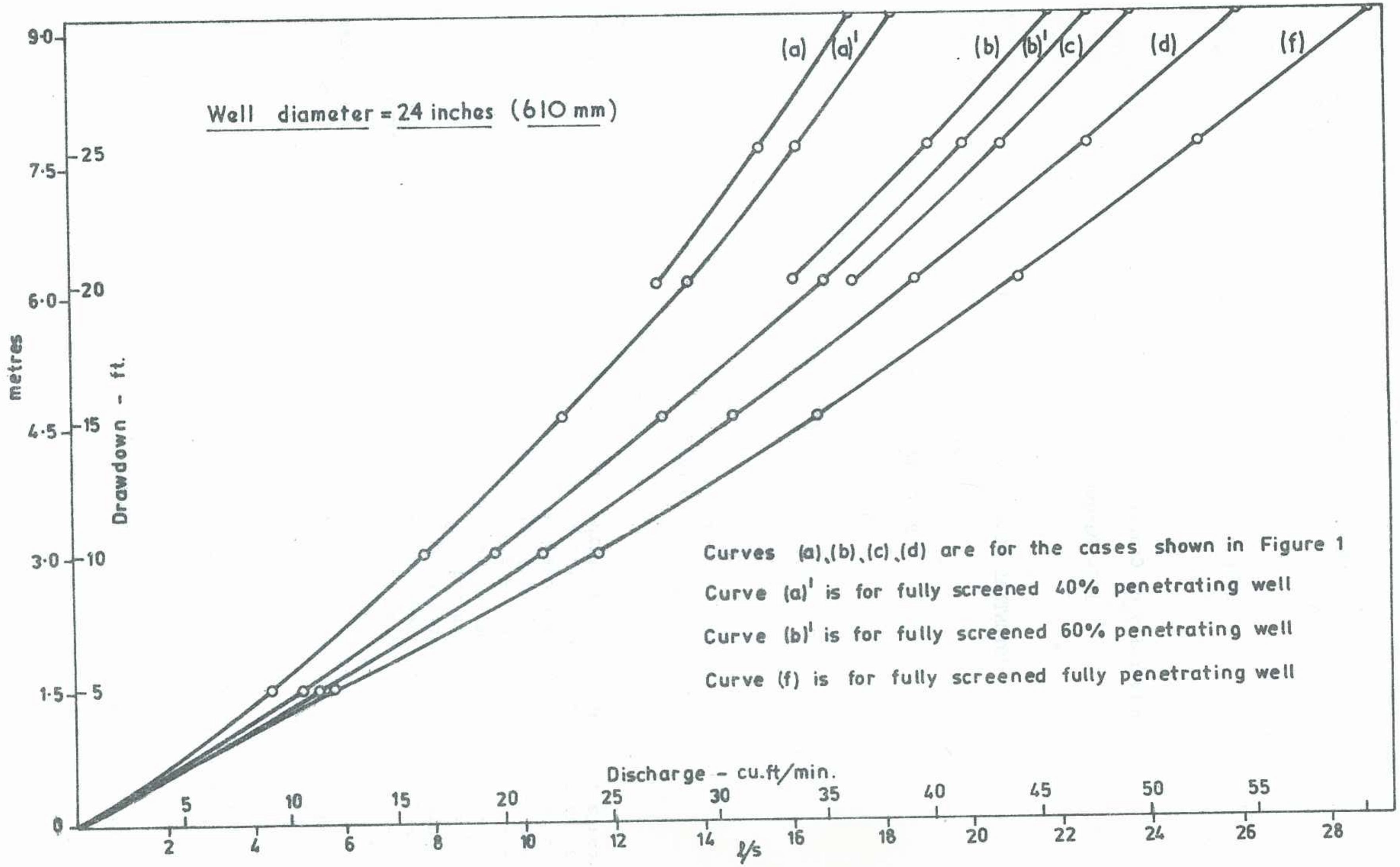

FIGURE 3: EFFECT OF SCREEN LENGTH AND POSITION ON DRAWDOWN - DISCHARGE RELATIONSHIP