Hydraulic Behavior of Dam Cores Compacted of Non-Plastic Materials

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ABSTRACT
The data resulted from monitoring of a series of earth dam cores constructed of non-plastic moraine tills are studied and analyzed. in many of these cores, a common anomaly was observed. The piezometric readings were considerably different with expected values obtained by theoretical seepage analysis. In the upstream side of cores, during the reservoir filling and in the early years of service, the reading values were higher than expected values, while they were lower in the downstream side. By the time, the differences in pore pressure were reduced, and after some years, the piezometric readings matched the expected pore pressure at respected positions.

The results of analysis show that the magnitude of the observed anomaly, is a function of the following parameters: the geometry of the core, the water content of material at the time of compaction, the height of the dam, the grading curve of used material and the rate of reservoir filling.

Keywords: earth dams, piezometer, water content, non-plastic material, compaction

RESUME
Les donnés d'osculation de noyau de quelques barrages en terre construits des moraines non plastiques sont examinés. Dans plusieurs de ces barrages, on a observé une anomalie des donnés piézométriques. Les piézomètres situés au coté amont, durant la période de mise en eau et les premières années d'exploitation, ont montré des valeurs beaucoup plus élevés que les valeurs théoriques expectatifs, i.e. une surpression. Tandis qu'au coté aval, les pressions interstitielles étaient plus petites. Au fur et à mesure, la différence observée a était diminué et les donnés piézométriques tendaient ver les valeurs théoriques expectatifs. Les analyses montrent que la surpression observée dans ce type de barrages est reliée aux paramètres suivants: la géométrie du noyau, la teneur en eau des matériaux au moment de compactage, la hauteur du barrage, la granulométrie des matériaux et le taux de remplissage du réservoir.

Mots clés: barrages en terre, piézomètre, teneur en eau, matériel non plastique, compactage

1. INTRODUCTION

In a zoned dam, the core dissipates the energy of the infiltrating water and brings it down from the reservoir level potential to a lower potential equal to the elevation at the downstream side. Based on this hypothesis, pore water pressure should decrease more or less linearly from the upstream to the downstream side of the core and thus, the distribution of equipotential lines should be quasi-uniform, as shown in Figure 1.

For several large zoned earth dams, it has been reported that the pore pressures in the cores were significantly in excess of the expected values after the first filling of the reservoir. Furthermore, the pore pressures remained close to the reservoir potential in a large portion of the core, even near the downstream face. Such dams are located in Canada, in Scandinavian countries, and in Australia. Their cores are built of glacial till, moraine, and their heights are large. Figure 2 shows the above peculiarity in the core of LG-4 dam in northern Quebec, Canada.

The presence of such high pore pressures has created anxiety in relation to the mechanical performance of the core and the possible presence of fracture. Furthermore, the high pore pressure causes a decrease in effective stress throughout the core and may affect the mechanical stability of the dam. It may also increase the risk of piping and internal erosion within the core, due to the high hydraulic gradients in the downstream part of the core. A better understanding of these phenomena will help to determine whether such situations present any risks.

2. CASE HISTORIES

Five case histories of unexpected distribution of core pore pressure are briefly presented in this section.

LG-4 (Canada) is a 125 m high zoned dam composed of a glacial silty sand central core of moderate width protected by upstream and downstream filters, gravely shells, and rockfill shoulders. Figure 2-*a* shows the equipotential lines at the end of reservoir filling (Verma et al. 1985). The distribution of equipotential lines is not uniform and they

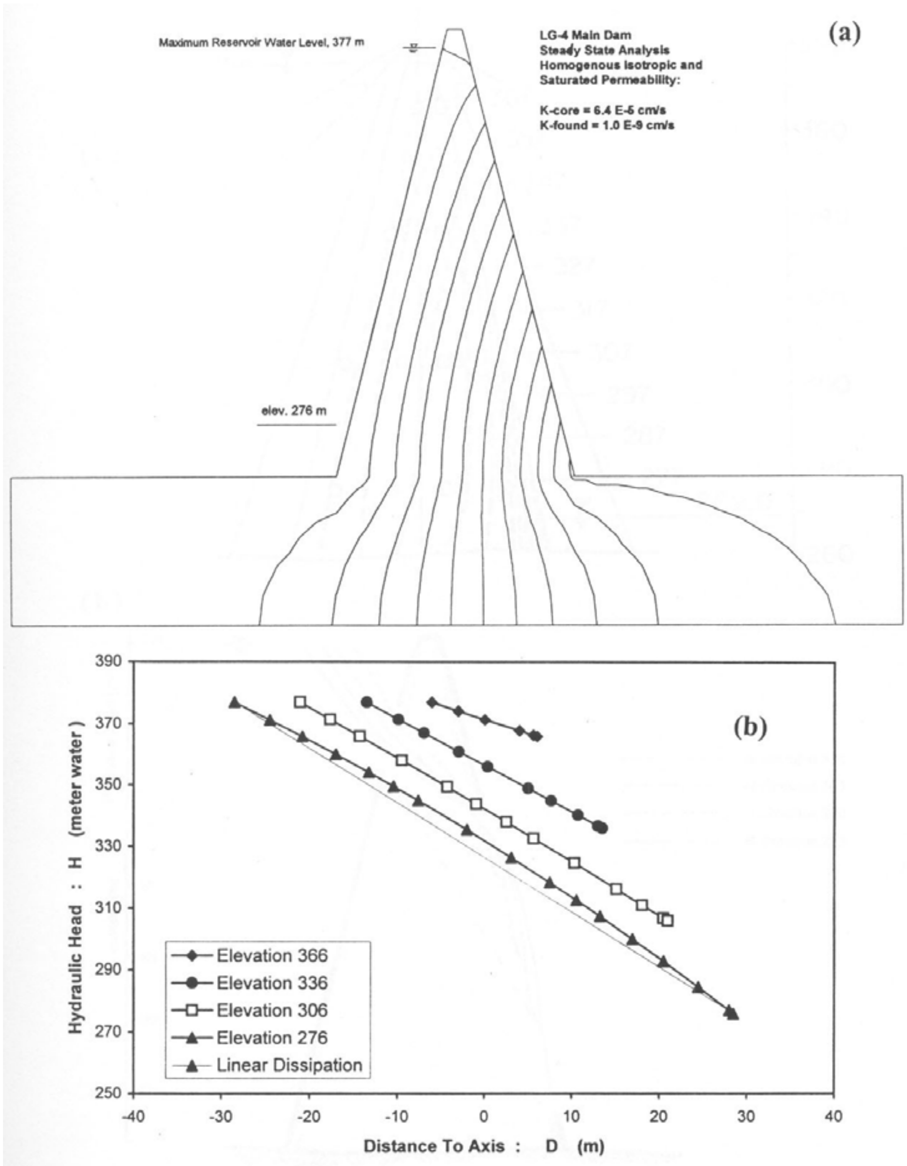

Figure 1. Theoretical seepage analysis for LG-4 dam core: a) distribution of equipotential lines; b) profile of potential across the core at different elevations.

are mostly concentrated near the downstream face. Figure 2-*b* shows a much greater gradient in the downstream face, while the gradient is much smaller in the rest of the core, especially in the central part.

W.A.C. Bennet Dam (Canada), with 183 m height, is one of the highest and largest earth dams in the world. This is a zoned dam with a very thick glacial silty sand core, protected by a sandy gravel filter and gravel drain at downstream, supported by sandy gravel shells and gravel sand transition zones. Taylor et al (1985), (Taylor et al. 1985), drew equipotential lines, on the basis of a finite element analysis, 11 years after impounding. The analysis was done through trial of various combinations of anisotropy and permeability and taking into account the foundation conditions such that a good agreement was obtained with the observed data. As shown, in Figure 3, a high concentration of equipotential lines between the downstream piezometers and the downstream face of the core is evident.

Vatendalsvatn Dam (Norway) is a 125 m high dam with a central thin core of till protected by a sandy gravel filter, supported by rockfill shells and transitions (Myrvoll et al. 1985). During the cyclic impounding, the gradient across the core was quite steep and most of the head was lost in

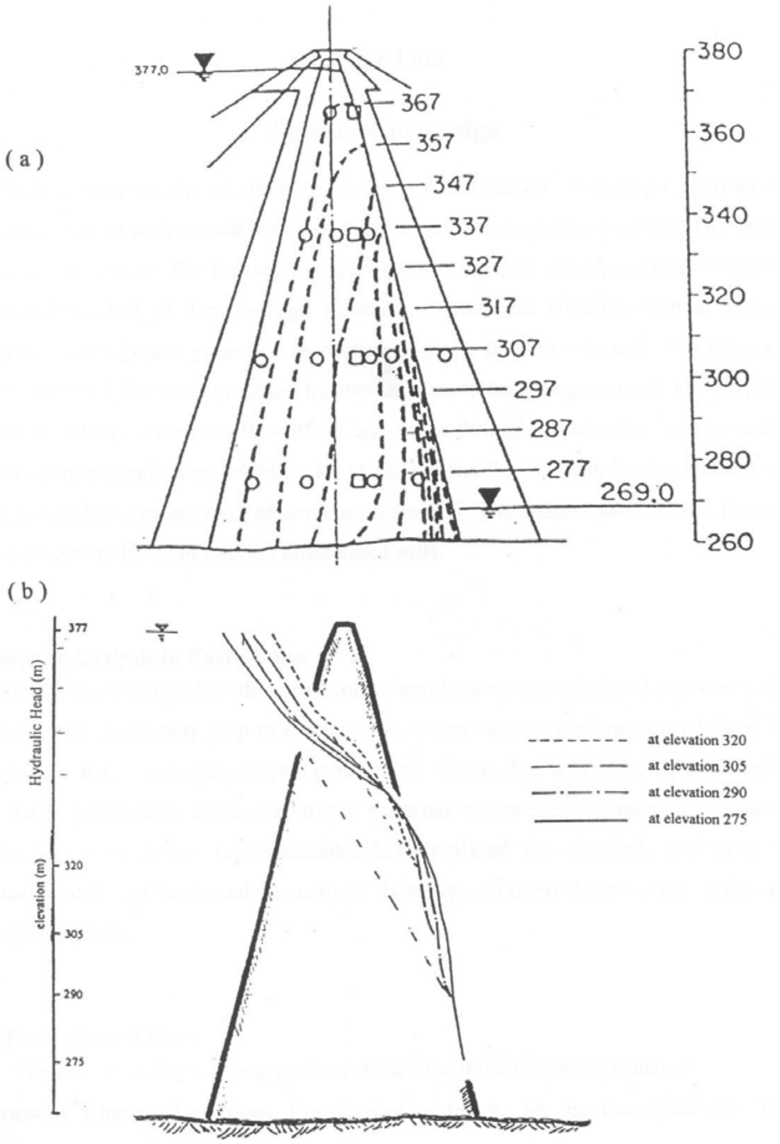

Figure 2. Observed potential in LG-4 dam core at the end of reservoir filling: a) distribution of equipotential lines (Verma et al. 1985); b) profile of potential across the core at different elevations

a narrow zone near the downstream face. With time, the gradient became less pronounced. Nevertheless, at the end of impounding when the reservoir was at its maximum level, the distribution of head loss across the core was still not uniform. Figure 4 shows the equipotential lines based on piezometric observation data, for the first maximum reservoir level almost two years after construction. The figure shows a smooth loss of head through the upstream two thirds of the core, while a significant portion of the head loss is concentrated in the downstream strip of the core. In the latter portion, the equipotential lines are quite vertical comparing to the expected typical inclined lines shown in Figure 1.

LG-2 (Canada) main dam is 150 meter high. Its slightly inclined core is relatively thin and built of till (Dascal O. 1995). The piezometric readings in the core just after the first maximum water level of the reservoir show much more head loss in the downstream part of the core. Figure 5 shows the profile of total head across the core at three different levels. The head distribution deviates from linearity and the gradient raises significantly near the downstream face, especially in the lower part of the core.

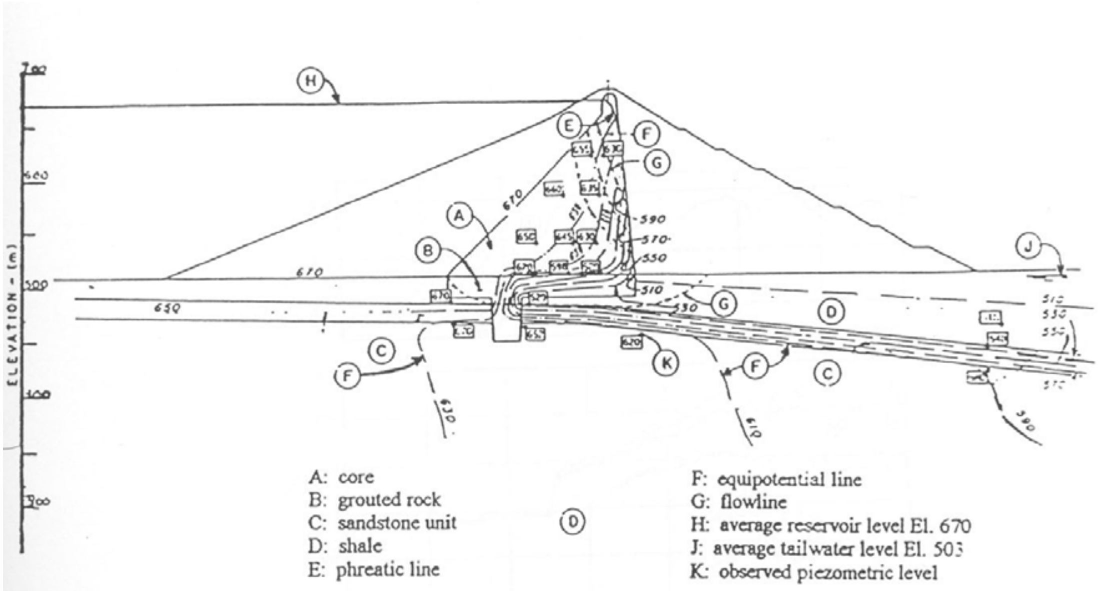

Figure 3 Equipotential lines in WAC Bennet dam eleven years after filling (Taylor et al. 1985).

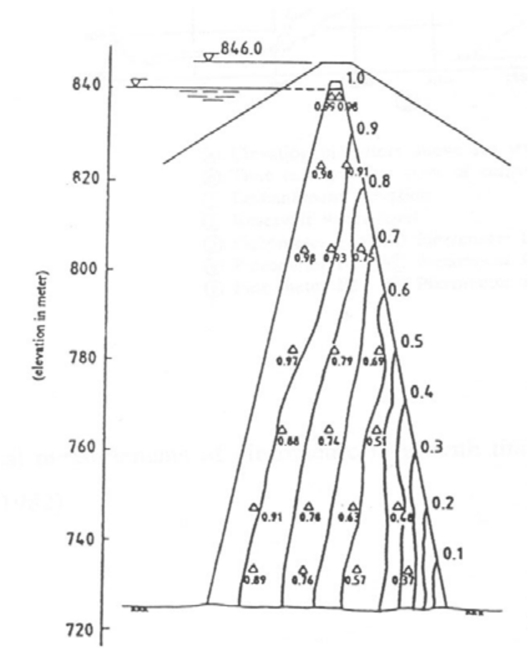

Figure 4. Equipotential lines in Vatendalsvatn dam core (Myrvoll et al. 1985).

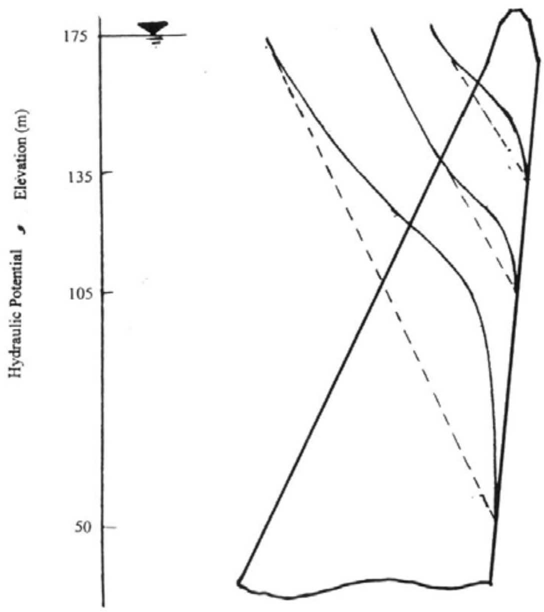

Figure 5. Profile of potential at different elevations across LG-2 dam core (Davoudi, M.H. 1999.)

Svartevanne Dam (Norway) is an earth-rockfill dam with maximum height of 129 m, with a moraine till core, fine-grained rockfill transition zones and coarse rockfill shells. Pore pressure during the construction stage was very small. Figure 6 shows the piezometric readings at two different levels after the impoundment. At each level, the loss of energy between the first and the second piezometer is much less than that of the second and the third one. This means that most of the head loss takes place in the downstream band of the core (Dibiago et. al. 1982)

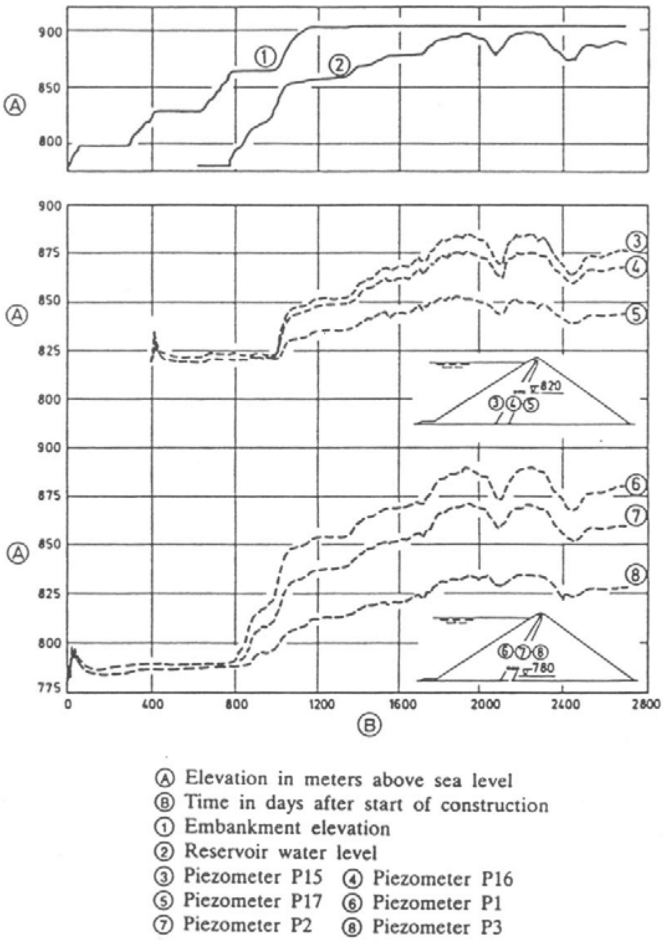

Figure 6. Equipotential lines in Svartevann dam core (Dibiago et al.1982).

3. FACTORS INFLUENCING HIGH PORE PRESSURE IN DAM CORES

This anomaly has been observed mainly in large dams having a central core built of relatively coarse material. Reports of the five dams show that their degree of saturation prior to impounding is relatively low, that is, between 46% and 77%. Their relatively great height, namely between 125 m and 183 m, causes a very significant difference in pore pressure between the upstream and downstream faces of the core, both during and after reservoir filling. After impoundment, the pore pressure reduces only slightly from the upstream face to the vicinity of the downstream face of the core, then drops sharply to atmospheric pressure at the downstream face. However, as there is more seepage through the core, the observed over pressure reduces towards the expected steady state values and more or less uniform pore pressure distribution is achieved. In most of the cases, seepage discharge increases in a period of time during the evolution of pore pressure.

Some characteristics of these cores are presented in Table 1. In this table, the first three columns present the average gradient (i), the mean degree of saturation at the end of construction (S) and the mean percentage of fines in the cores.

In all the cores, the maximum over pressure has been detected at the extreme downstream and at the lowest piezometric point. The elevation of this piezometer is presented in the fourth column. The core width (L) and the full reservoir head (Hr) at this elevation are shown in columns five and six. Column seven presents the distance of the piezometer from the upstream face of the core (D). The difference between the recorded pore pressure and the expected pore pressure is termed as “over pressure”. The maximum over pressures (M.O.P) and the decrease of the over pressure during the following two years (R.P) are also recorded. Some relationships between these parameters are illustrated in Figure 7 (Davoudi 1999). It should be noted that the scattered points, observed in a few cases, represent the Vatendalsvat Dam. The reservoir impoundment of this dam was quite different than the others. In other four dams, the reservoir was filled almost within one year, while it took more than four years for this dam. Furthermore, during the impoundment years, the main portion of reservoir was emptied each year, while the released water was negligible in the other dams. This difference might affect the distribution and the rate of over pressure in the core, and could cause a different behavior.

Table 1. Some characteristics of the cores made of till in Canada and Norway

Dam	LG-2	WAC	LG-4	Vatend-alsvatn	Svarte-vanne
Average Gradient	2.2	1	1.9	2.25	5
Initial Degree of Saturation: S (%)	46.5	55.8	60	71	77
Fine Particles (%)	-	28	30	30.5	-
Elevation (m)	43	512	276	731	780
Core Width: L (m)	61	160	58	49	25
Reservoir Head (m)	132	160	101	109	119
Distance From Upstream: D (m)	53	124	49	42	21
Maxim. Over Pressure: M.O.P.(m)	43	58	45	23	35
Released Pressure After 2 Years R.P.(m)	20	10	10	-	6

A general tendency between the maximum over pressure and the reservoir head as well as the core width is observed. The larger the reservoir pressure and the core width, the higher the over pressure is. Figure 7-*c* and *d* show the increase of over pressure with the reservoir head and the core width separately. The geometry of the core also seems to influence the presence of over pressure. Figure 7-*e* shows the decrease of over pressure with the average gradient in the core.

As shown in Figure 7-*f*, a general downward tendency between the maximum over pressure and the percentage of fine particles is revealed, indicating that the structure of the soil may affect the distribution of pore pressure in the core.

Figure 7-*a* shows the variation of maximum over pressure in terms of percentage of reservoir head, as a function of the degree of saturation after compaction. The over pressure increases as the degree of saturation increases. However, for high degrees of saturation, the over pressure decreases. The degree of saturation prior to reservoir filling may also affect the rate of pressure release during the operation years. Figure 7-*b* shows that the ratio of released pressure to average gradient of core (R.P/ i) decreases with the initial degree of saturation.

4. CONCLUSION

The results show that the excess pressure observed in cores compacted of non-plastic materials is related to the geometry of the core, the compaction condition of materials, the grading curve of used material, the degree of saturation of the core prior to impoundment, the reservoir filling regime and the seepage water volume through the core. The value of over pressure is related directly to the reservoir head and the core width, wile inversely to the percentage of fine particles. The rate of released pressure decreases with the degree of saturation of the core prior to impoundment. However, more research is needed to reveal the main cause of the presence of the excess pore pressure.

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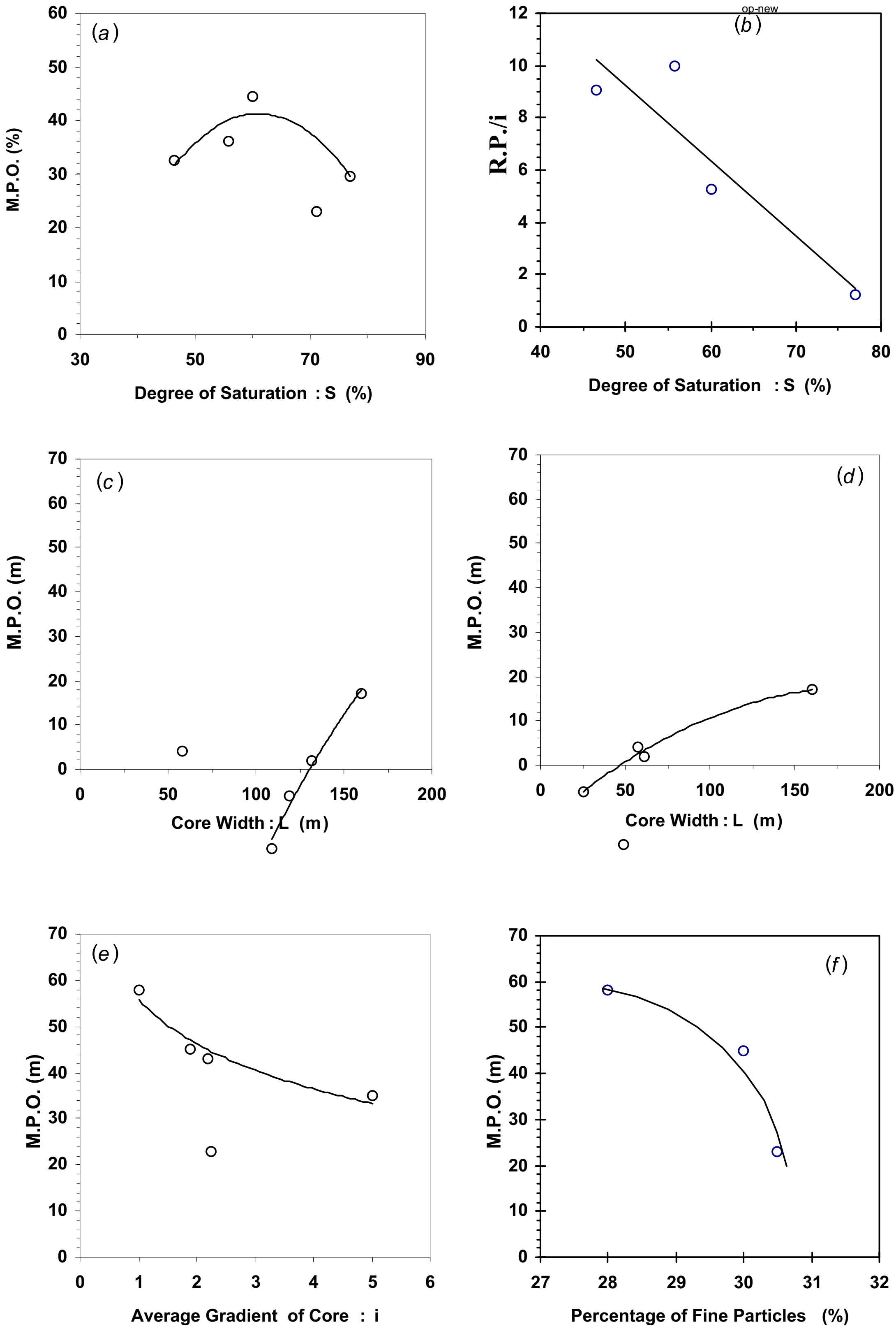
(a)
M.P.O. (%)
0
10
20
30
40
50
60
30
50
70
90
Degree of Saturation : S (%)
op-new
(b)
R.P./i
0
2
4
6
8
10
12
40
50
60
70
80
Degree of Saturation : S (%)
(c)
M.P.O. (m)
0
10
20
30
40
50
60
70
0
50
100
150
200
Core Width : L (m)
(d)
M.P.O. (m)
0
10
20
30
40
50
60
70
0
50
100
150
200
Core Width : L (m)
(e)
M.P.O. (m)
0
10
20
30
40
50
60
70
0
1
2
3
4
5
6
Average Gradient of Core : i
(f)
M.P.O. (m)
0
10
20
30
40
50
60
70
27
28
29
30
31
32
Percentage of Fine Particles (%)

Fig. 7