

Copyright is owned by the Author of the thesis. Permission is given for a copy to be downloaded by an individual for the purpose of research and private study only. The thesis may not be reproduced elsewhere without the permission of the Author.

**HYDRAULIC
FACTORS LIMITING THE USE OF
SUBIRRIGATION IN FINE TEXTURED SOILS**

A thesis
submitted in partial fulfilment
of the requirements for the degree

of

Master of Philosophy

in

Agricultural Engineering

at

Massey University, Palmerston North,
New Zealand

Babar Mahmood

1996

ABSTRACT

Subirrigation is a method of supplying water directly to the plant root zone under the ground surface by means of subsurface drains which are also used to remove excess water from the root zone. Subsurface drainage systems are used to maintain appropriate levels of soil moisture in the root zone of a crop by managing the water table. Subirrigation is seen as being an economic alternative to conventional sprinkler irrigation systems on dairy farms where mole drainage systems are already installed. However, information on subirrigation of these fine textured soils is very limited. The primary focus of this study was to evaluate the hydraulic parameters limiting the use of subirrigation in fine textured soils.

A field experiment was carried out on the Massey University No. 4 Dairy Farm in Palmerston North. During the study, a subsurface tile drainage system, with mole channels, was used to subirrigate 1248 m² of Tokomaru silt loam soil. The depth of irrigation applied was 185.71mm (232 m³ of water added to the system). Time Domain Reflectometry (TDR) was used to measure the soil moisture content to a depth of 400mm at three positions, 5 m away from the drainage lateral and at three control points in an adjacent unirrigated plot. A theoretical daily water balance was developed for the irrigated plot and unirrigated control, based on the available weather data.

The results from field experiment showed that sufficient water did not move from the drainage lateral to the moles. Reasons for this may include: (a) Not enough water applied, (b) Not enough pressure head was available to force water from the drainage lateral to the moles or (c) hydraulic conductivity of the backfill was too low.

Having identified, from the field experiment, that the hydraulic connection between the lateral and mole was a potential problem, a bin model experiment was carried out in the hydraulic laboratory of the Agricultural Engineering Department. Two different backfill materials (gravel and tokomaru silt loam soil) were used with two mole positions in the

bin relative to the drainage lateral. The flow rate and head losses through the system were measured for different applied pressure heads. The saturated hydraulic conductivity (K_{sat}) of the backfill materials were measured in the laboratory and were measured other relevant physical properties (bulk density, particle density and porosity).

The bin model experiment showed that flow rate through the system increases as the pressure head increases for both gravel and Tokomaru silt loam soil backfills. The flow rate with gravel backfill was eight times more than the flow rate with Tokomaru silt loam soil.

For a gravel backfill the efficiency of hydraulic connection between the lateral and moles must only be in the order of 2 to 3% for successful subirrigation. With a backfill of Tokomaru silt loam the efficiency of connection must be 10 to 20%. This may not be achieved in the field as the hydraulic conductivity of the backfill will be of a similar magnitude to the surrounding soil leading to significant water losses vertically downward as well as horizontally.

It is recommended that further field studies be conducted using gravel backfill. Further laboratory studies using other alternative backfill materials are also suggested.

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude and indebtedness to my chief supervisor, Dr. Colin Wells, for his thoughtful advice, guidance, kind assistance, perceptive questioning and support at every stage of this study. The completion of this study could not have been possible without the friendship, inspiration and encouragement that I received from my chief supervisor Dr. Colin Wells and for these, I am particularly grateful. My sincere thanks and appreciation are due to Dr. David Horne, my co-supervisor, for his valuable suggestions during the investigation.

My special thanks to Professor Gavin Wall, the Head of Department of Agricultural Engineering, for his interest and valuable suggestions during the research. I would like to thank the members of the Department of Agricultural Engineering, for their encouragement; to Mr. Ian Painter, Mr. Leo Bolter, Mr. Dave Robinson, Mr. Russell Watson, and Mr. Gerald Harrigan for their help in constructing the field experiment and laboratory experimental model.

I would like to thank Mr. David Haskell, Versatile Plastic Recyclers Limited, Otaki, for supplying the plastic material.

My special thanks are due to the New Zealand Government through the Overseas Development Assistance (NZODA) programme for the award of Postgraduate Scholarship which made it possible for me to pursue this M.Phil study. I am grateful for the moral support of numerous friends and in particular Mr. Tasneem, Mr. Shahbaz, and Dr. Manzoor-ul-Haq Awan. I would like to extend my sincere thanks to all my fellow-students in the Department of Agricultural Engineering and my flat mates for their help, moral support and joyful company.

Finally, my deepest gratitude and thanks to my father, brother and sisters whose love, patience and constant encouragement have been invaluable during my study in New Zealand.

TABLE OF CONTENTS

ABSTRACT	ii
ACKNOWLEDGEMENT	iv
TABLE OF CONTENTS	v
LIST OF TABLES	
LIST OF FIGURES	
CHAPTER 1	
INTRODUCTION AND OBJECTIVES	1
1.1 The New Zealand Situation	1
1.2 Subirrigation Systems	2
1.2.1 Principle of operation	2
1.2.2 Requirements for subirrigation	5
1.2.3 Advantages of subirrigation	5
1.2.4 Disadvantages of subirrigation	6
1.3 Problem Statement	7
1.4 Aim of the Study	8
1.5 Approach of Analysis	8
1.6 Outline of the Thesis	9
CHAPTER 2	
LITERATURE REVIEW	10
2.1 Design Features and Criteria for Subirrigation System	10
2.1.1 Critical factor in the design of subirrigation system	12
2.1.2 Lateral spacing	12
2.2 Life of Mole Drains	14
2.3 Locations of the Subirrigation Practice	15
2.3.1 Subirrigation in humid regions	15
2.3.2 Developing subirrigation in humid regions	16
2.3.3 Subirrigation in arid and semiarid regions	16

2.3.4	Developing subirrigation in arid and semiarid regions	18
2.4	Economic, Production and Environmental Impacts of Subirrigation and Controlled Drainage	18
2.4.1	Economic and production impacts	19
2.4.2	Environmental impacts	22
2.5	Over Drainage Problem	22
2.6	Water Table Management Models	23
2.7	Water and Energy Requirements for Surface and Subsurface Irrigation Systems	24
2.8	Effect of Gravel Backfill on Flow Rate	25
2.9	Effect of Fabric Wrap Envelope and Drain Slope	26
2.10	Effect of Hydraulic Conductivity on Yield for Subirrigation System	27
2.11	Head Losses in Subirrigation System	27
2.12	Subirrigation in Fine Textured Soils	28

CHAPTER 3

FIELD EXPERIMENT		31
3.1	Objectives	31
3.2	Description of Site	31
3.2.1	Soil type	32
3.2.2	Climate	34
3.2.3	Existing drainage system	35
3.3	Trial Site and Equipment Set up	35
3.3.1	Site layout	35
3.3.2	Sump	36
3.3.3	Pump	37
3.3.4	Flow meter	37
3.3.5	Time Domain Reflectometry probes	37
3.3.6	Observation wells	37
3.4	Method	37
3.5	Results	39

3.6	Discussion	43
3.7	Conclusions	45

CHAPTER 4

LABORATORY EXPERIMENT		46
4.1	Head Flow Measurements in Laboratory Model	46
4.1.1	Objectives	46
4.1.2	Equipment	47
4.1.2.1	The Bin	47
4.1.2.2	Lateral	47
4.1.2.3	Mole	47
4.1.2.4	Constant head system	47
4.1.2.5	Flow meter	49
4.1.2.6	Backfill treatments	50
4.1.3	Method	50
4.1.3.1	No backfill with bottom mole position	50
4.1.3.2	Gravel backfill with bottom mole position	51
4.1.3.3	Gravel backfill with top mole position	52
4.1.3.4	Tokomaru silt loam soil backfill with top mole position	53
4.1.3.5	Tokomaru silt loam soil backfill with bottom mole position	54
4.1.4	Results	54
4.1.4.1	No backfill	54
4.1.4.2	Results with backfill material	55
4.1.5	Discussion	61
4.1.6	Development of a simple model	64
4.2	Determination of Saturated Hydraulic Conductivity	75
4.2.1	Theory	75
4.2.1.1	Constant head determination	75
4.2.1.2	Falling head determination	78

4.2.2	Equipment	79
4.2.3	Method	79
4.2.3.1	Saturated hydraulic conductivity of gravel	79
4.2.3.2	Saturated hydraulic conductivity of H.D.P.E (milk bottle plastic chips)	81
4.2.3.3	Saturated hydraulic conductivity of H.D.P.E (commodity bottle plastic chips)	81
4.2.3.4	Saturated hydraulic conductivity of Tokomaru silt loam soil	81
4.2.4	Results	84
4.2.5	Discussion	86
CHAPTER 5		
GENERAL DISCUSSION		93
CHAPTER 6		
CONCLUSIONS AND RECOMMENDATIONS		97
6.1	Conclusions	
6.2	Recommendations for future research	98
BIBLIOGRAPHY		99
APPENDICES		
A1	Determination of Bulk density, Particle density, and Porosity	108
A1.1	Theory	108
A1.2	Equipment and Method	109
A1.3	Results and Discussion	110
A2	Particle Size Analysis of the Gravels, Milk Bottle Plastic Chips, Commodity Bottle Plastic Chips, and Tokomaru Silt Loam Soil	113
A2.1	Equipment and Method	113
A2.2	Results	113

LIST OF TABLES

Table

3.1	Theoretical daily water balance	40
3.2	Measured and predicted soil moisture content in irrigated and unirrigated plots	41
4.1	Head loss measurements with no backfill at bottom mole position	56
4.2	Head loss measurements with gravel backfill at bottom mole position	57
4.3	Head loss measurements with gravel backfill at top mole position	58
4.4	Head loss measurements with Tokomaru silt loam soil backfill at top mole position	59
4.5	Head loss measurements with Tokomaru silt loam soil backfill at bottom mole position	60
4.6	Constant (a , b) and correlation coefficient (%) between the predicted and measured flow rate for each backfill treatment and mole setting	65
4.7	Saturated hydraulic conductivity measurements for gravels	84
4.8	Saturated hydraulic conductivity measurements for milk bottle plastic chips	85
4.9	Saturated hydraulic conductivity measurements for commodity bottle plastic chips	85
4.10	Saturated hydraulic conductivity measurements for Tokomaru silt loam soil	86
4.11	Correlation coefficient (%) and constant (a , b) for different materials	92
5.1	Bulk density and K_{sat} values for different materials	96
5.2	Cost comparison between gravel and H.D.P.E material	96
A1.1	Bulk density, Particle density, and Porosity measurements of gravels	110
A1.2	Bulk density, Particle density, and Porosity measurements of Tokomaru silt loam soil sample taken from bin around the top mole position	111
A1.3	Bulk density, Particle density, and Porosity measurements of Tokomaru silt loam soil sample taken from bin around the bottom mole position	111

A1.4	Bulk density, Particle density, and Porosity measurements of milk bottle plastic chips	112
A1.5	Bulk density, Particle density, and Porosity measurements of commodity bottle plastic chips	112
A2.1	Particle size analysis measurements of gravels	113
A2.2	Particle size analysis measurements of H.D.P.E material (milk bottle plastic chips)	114
A2.3	Particle size analysis measurements of H.D.P.E material (commodity bottle plastic chips)	115

LIST OF FIGURES

Figures

1.1	Subsurface drainage system working in drainage mode	3
1.2	Subsurface drainage system working in subirrigation mode	4
3.1	The profile Tokomaru silt loam soil	33
3.2	Long term rainfall and evapotranspiration pattern in Palmerston North	34
3.3	An aerial photograph of the trial site	36
3.4	Theoretical daily water balance for the irrigated and unirrigated plots	42
3.5	In field experiment water did not reach to the mole level, but around the lateral it was quite dry	44
4.1	Setting of the mole and lateral in the bin	48
4.2	Bin model laboratory experiment	49
4.3	Gravel backfill with bottom mole position	51
4.4	Gravel backfill with top mole position	52
4.5	Raking of the Tokomaru silt loam soil sample	53
4.6	Head loss in the mole, lateral, and flow meter with no backfill at bottom mole position	55
4.7	Head loss in the mole, lateral, and flow meter with gravel backfill at bottom mole position	62
4.8	Head loss in the mole, lateral, and flow meter with gravel backfill at top mole position	62
4.9	Head loss in the mole, lateral, and flow meter with Tokomaru silt loam backfill at bottom mole position	63
4.10	Head loss in the mole, lateral, and flow meter with Tokomaru silt loam backfill at top mole position	63
4.11	A linear graph between measured flow rate and head relative to the bottom mole position with no backfill	66
4.12	A log-log graph between the measured flow rate and head relative to the	

	bottom mole position with no backfill	66
4.13	A linear graph between measured flow rate and head relative to the bottom mole position with gravel backfill	67
4.14	A log-log graph between the measured flow rate and head relative to the bottom mole position with gravel backfill	67
4.15	A linear graph between measured flow rate and head relative to the top mole position with gravel backfill	68
4.16	A log-log graph between the measured flow rate and head relative to the top mole position with gravel backfill	68
4.17	A linear graph between measured flow rate and head relative to the bottom mole position with Tokomaru silt loam soil backfill	69
4.18	A log-log graph between the measured flow rate and head relative to the bottom mole position with Tokomaru silt loam soil backfill	69
4.19	A linear graph between measured flow rate and head relative to the top mole position with Tokomaru silt loam soil backfill	70
4.20	A log-log graph between the measured flow rate and head relative to the top mole position with Tokomaru silt loam soil backfill	70
4.21	Correlation between the predicted and measured flow rates with no backfill at bottom mole position	71
4.22	Correlation between the predicted and measured flow rates with gravel backfill at bottom mole position	71
4.23	Correlation between the predicted and measured flow rates with gravel backfill at top mole position	72
4.24	Correlation between the predicted and measured flow rates with Tokomaru silt loam soil backfill at bottom mole position	72
4.25	Correlation between the predicted and measured flow rates with Tokomaru silt loam soil backfill at top mole position	73
4.26	Predicted flow rate vs head relative to mole position for different backfill treatments at bottom and top mole position	74
4.27	Constant head permeameter	77
4.28	Falling head permeameter	78

4.29	Saturated hydraulic conductivity of gravels	80
4.30	Saturated hydraulic conductivity of milk bottle plastic chips	82
4.31	Saturated hydraulic conductivity of commodity bottle plastic chips	83
4.32	A linear graph between the measured K_{sat} and the velocity of flow of water through the gravel	87
4.33	A linear graph between the measured K_{sat} and the velocity of flow of water through the milk bottle plastic chips	87
4.34	A linear graph between the measured K_{sat} and the velocity of flow of water through the commodity bottle plastic chips	88
4.35	A semi-log graph between the measured K_{sat} and the velocity of flow of water through the gravel	89
4.36	A semi-log graph between the measured K_{sat} and the velocity of flow of water through the milk bottle plastic chips	89
4.37	A semi-log graph between the measured K_{sat} and the velocity of flow of water through the commodity bottle plastic chips	90
4.38	Correlation between the measured and predicted K_{sat} values for gravel	90
4.39	Correlation between the measured and predicted K_{sat} values for the milk bottle plastic chips	91
4.40	Correlation between the measured and predicted K_{sat} values for the commodity bottle plastic chips	91