STRESSES GENERATED IN SOIL CRUST BY
EMERGING DICOT SEEDLINGS

DISSERTATION
Presented in Partial Fulfillment of the Requirements for
the Degree Doctor of Philosophy in the Graduate
School of The Ohio State University

By


* * * * * * * * * * * *

The Ohio State University
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Advisor
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Respectfully

Dedicated

to

My teachers
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*Extension publications

7. ibid, 1974.
8. ibid, 1975.

(vi)
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# TABLE OF CONTENTS

DEDICATION ........................................................................................................ ii
ACKNOWLEDGMENTS ......................................................................................... iii
VITA ....................................................................................................................... iv
LIST OF TABLES ................................................................................................. xi
LIST OF FIGURES ............................................................................................... xii
LIST OF SYMBOLS .............................................................................................. xiii

Chapter
1 INTRODUCTION ................................................................................................. 1
2 OBJECTIVES .................................................................................................... 5
3 REVIEW OF LITERATURE ............................................................................. 6
4 THEORETICAL ANALYSIS OF SURFACE STRESSES ................................. 18
   4.1 Introduction ............................................................................................. 18
   4.2 Governing equations ............................................................................. 19
   4.3 Stress analysis ....................................................................................... 21
5 SOYBEAN SEEDLING EMERGENCE FORCE ............................................ 25
   5.1 Experimental design ............................................................................. 25
   5.1.1 Selection of physical parameters .................................................... 26
   5.1.2 Formation of pi-terms ..................................................................... 31
   5.1.3 Development of prediction equations ............................................. 31
   5.1.4 Experimental schedule ................................................................... 34
   5.2 Experimental methods ......................................................................... 34
   5.2.1 Seedling force measurements .......................................................... 34
   5.2.2 Hypocotyl diameter measurements ................................................ 45
   5.2.3 Critical time measurements .............................................................. 45
   5.2.4 Energy content determinations ......................................................... 45
   5.3 Discussion and results .......................................................................... 49
   5.3.1 Effect of seed moisture on critical time ......................................... 49
   5.3.2 Effect of soil moisture on critical time .......................................... 51
   5.3.3 Effect of seed moisture on seedling force ...................................... 51
   5.3.4 Effect of soil moisture on seedling force ....................................... 54
   5.3.5 Generalized prediction equations ................................................... 54
   5.3.6 Hypocotyl diameter studies ............................................................. 57
6 MECHANICAL PROPERTIES OF SOIL CRUST ........................................... 60
   6.1 Modulus of rupture of soil crust ......................................................... 60
   6.2 Bulk density of soil crust ..................................................................... 63
   6.3 Soil crust thickness .............................................................................. 66
   6.4 Poisson's ratio and modulus of elasticity ............................................ 71
   6.5 Sub-soil reaction modulus ................................................................. 71

(viii)
7 PREDICTION OF SOIL CRUST BENDING STRESSES

7.1 Surface bending stresses in soil crust

7.2 Interpretation of results

7.2.1 IIa4 versus II8

7.2.2 IIa4 versus II10

7.2.3 IIa4 versus II12

7.2.4 IIa4 versus II13

7.2.5 IIa4 versus II14

7.3 Application of results

7.3.1 Management techniques in crusted soils

7.4 Summary of results of this study

8 CONCLUSIONS

9 SUGGESTIONS FOR FURTHER STUDIES

BIBLIOGRAPHY

APPENDICES

A. Mechanical analysis of crusty silt loam soil

B. Moisture equivalent curve

C. Mean emergence force data

D. Critical time data

E. Observed and predicted values of critical time and seedling force number

F. Hypocotyl diameter data

G. Modulus of rupture of soil crust

H. Bulk density determination data

I. Bulk density versus sample thickness data

J. Poisson's ratio and Young's modulus data

SUMMARY
LIST OF TABLES

1. Results on maximum seedling emergence force and critical time (1950-1978) .................................................. 9
2. Pi-terms for stresses generated in soil crusts by emerging dicot seedlings ...................................................... 23
3. Physical parameters for seedling force system ......................... 27
4. Physical parameters for critical time system .......................... 27
5. Pi-terms for seedling force and critical time systems ............... 32
6. Experiment schedule for seedling force and critical time studies ................................................................. 35
7. Relationships between hypocotyl diameter and temperature ...... 58
8. Soybean planting recommendations in Ohio .......................... 79
9. Values of pi-terms for bending stress number ....................... 80
10. Maximum bending stress values generated in soil crusts by emerging soybean seedling ..................................... 89
LIST OF FIGURES

1. Schematic diagram of soybean seed ........................................... 7
2. Process of soil crust formation ................................................ 12
3. Failure mechanisms of crusted soils (Arndt, 1965a) ................... 16
4. Dicot seeding and soil-crust system ....................................... 20
5. Strain gage signal conditioner and power supply ..................... 36
6. Emergence unit with force transducer .................................... 37
7. Instrumentation for soybean seedling force studies .................. 38
8. Preparation of soil used in the seedling force studies ............... 40
9. Lower face of upper emergence force unit ................................ 41
10. Compaction unit to compact soil in the upper unit .................... 42
11. Seedling force units during the test run .................................. 44
12. Block diagram of seedling force measurement procedure ........... 46
13. Determination of mean seed diameter of soybean .................... 47
14. Oxygen bomb calorimeter ...................................................... 48
15. Critical time vs seed moisture .............................................. 50
16. Critical time vs soil moisture ............................................... 52
17. Seedling force number vs seed moisture .................................. 53
18. Seedling force number vs soil moisture .................................. 55
19. Hypocotyl diameter vs temperature ....................................... 59
20. Rainfall simulator ............................................................... 61
21. Soil samples receiving the heat treatment ............................... 62
22. Soil crust sampling procedure .............................................. 64
23. Modulus of rupture of soil crust .......................................... 65
24. Coating of soil crust sample ............................................... 67
25. Weighing coated crust sample in air ..................................... 68
26. Weighing coated crust sample in water .................................. 69
27. Bulk density vs soil crust thickness ..................................... 70
28. Preparation of simulated soil crust sample ............................. 72
29. Strain gages on soil crust sample ......................................... 73
30. Simple bending test to determine V and E ................................ 74
31. Instrumentation to determine V and E .................................... 75
32. Sub-soil reaction modulus .................................................... 76
33. Bending stress number vs $\Pi_g$ ........................................... 82
34. Bending stress number vs $\Pi_{10}$ .......................................... 83
35. Bending stress number vs $\Pi_{12}$ .......................................... 84
36. Bending stress number vs $\Pi_{13}$ .......................................... 86
37. Bending stress number vs $\Pi_{14}$ .......................................... 87

(xi)
List of Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pa</td>
<td>Pascal</td>
</tr>
<tr>
<td>N</td>
<td>Newton</td>
</tr>
<tr>
<td>m</td>
<td>Meter</td>
</tr>
<tr>
<td>cm</td>
<td>Centimeter</td>
</tr>
<tr>
<td>kg</td>
<td>Kilogram mass</td>
</tr>
<tr>
<td>g</td>
<td>Gram mass</td>
</tr>
<tr>
<td>J</td>
<td>Joule</td>
</tr>
<tr>
<td>kgf</td>
<td>Kilogram force</td>
</tr>
<tr>
<td>t</td>
<td>Elapsed time, hours</td>
</tr>
<tr>
<td>db</td>
<td>Dry basis</td>
</tr>
<tr>
<td>G</td>
<td>Gravitational field strength, N/kg</td>
</tr>
<tr>
<td>r</td>
<td>Correlation coefficient</td>
</tr>
<tr>
<td>d</td>
<td>Mean seed diameter, m</td>
</tr>
<tr>
<td>k</td>
<td>Constant of proportionality in the Universal Law of Gravitation</td>
</tr>
<tr>
<td>w</td>
<td>Deflection of plate (soil crust) due to force exerted by seedling, m</td>
</tr>
<tr>
<td>x,y</td>
<td>Position coordinates, m</td>
</tr>
<tr>
<td>a</td>
<td>Row spacing, m</td>
</tr>
<tr>
<td>b</td>
<td>Seed spacing down the row, m</td>
</tr>
<tr>
<td>P</td>
<td>Maximum seedling force exerted by dicot seedling, N</td>
</tr>
<tr>
<td>c</td>
<td>Hypocotyl radius of dicot seedling, m</td>
</tr>
<tr>
<td>Q</td>
<td>Distribution of force P over an area $\pi C^2$, N/m²</td>
</tr>
<tr>
<td>u</td>
<td>Side of equivalent square, $u^2 = \pi C^2$, over which P is distributed, m</td>
</tr>
<tr>
<td>h</td>
<td>Soil crust thickness, m</td>
</tr>
<tr>
<td>L</td>
<td>Length of simulated crust sample, m</td>
</tr>
<tr>
<td>B</td>
<td>Width of simulated soil crust sample, m</td>
</tr>
<tr>
<td>H</td>
<td>Thickness of simulated soil crust sample, m</td>
</tr>
<tr>
<td>e</td>
<td>Sinkage of plate (5 x 5 cm) due to applied load $P_2$, m</td>
</tr>
<tr>
<td>$E_1$</td>
<td>Internal energy of the dry seed, J/kg</td>
</tr>
<tr>
<td>$J_1$</td>
<td>Mechanical equivalent of heat, N m/J</td>
</tr>
<tr>
<td>$m_1$</td>
<td>Initial mass of the dry seed, kg</td>
</tr>
<tr>
<td>$t_c$</td>
<td>Critical time (time at which seedling attains its maximum force), hours</td>
</tr>
<tr>
<td>$t_g$</td>
<td>Characteristic time factor of growth, hours</td>
</tr>
<tr>
<td>$\theta_a$</td>
<td>Environmental temperature, °C</td>
</tr>
<tr>
<td>$\theta_L$</td>
<td>Temperature below which germination is less than 50%, 5°C</td>
</tr>
<tr>
<td>$\theta_H$</td>
<td>Temperature above which germination is less than 50%, 45°C</td>
</tr>
<tr>
<td>$r_1$</td>
<td>Distance between the seed mass and center of the earth, m</td>
</tr>
<tr>
<td>$R^2$</td>
<td>Coefficient of determination</td>
</tr>
<tr>
<td>$C_1$</td>
<td>Soil (Crosby silt loam) impedance, kPa</td>
</tr>
<tr>
<td>$f_1$</td>
<td>Seedling emergence force per seedling, N</td>
</tr>
</tbody>
</table>
\( q' \) Distributed load due to weight of soil crust, N/m²

\( E_c \) Modulus of elasticity of soil crust, N/m²

\( D \) Modulus of rigidity of soil crust, \( = (E_c h^3)/12 (1 - V^2) \), N·m

\( k_1 \) Sub-soil reaction modulus, N/m³

\( A_{mn} \) Fourier coefficient

\( \rho_b \) Dry bulk density of soil crust, g/cm³

\[ \begin{align*}
\tau_{xx} \\
\sigma_{xy} \\
\sigma_{yy}
\end{align*} \] Stress field on the crust surface due to force \( P \), N/m²

\( P_1 \) Applied load on the simulated soil crust sample, N

\( P_2 \) Applied load on crosby silt loam soil, N

\( e_a \) Axial strain on the surface of simulated crust sample, micro-m/m

\( e_t \) Transverse strain on the surface of simulated crust sample, micro-m/m

\( \sigma_1 \) Bending stress developed in the simulated crust sample due to applied load \( P_1 \), N/m²

\( \sigma_2 \) Stresses due to applied load \( P_2 \), N/m²

\( \Pi_1 \) Independent pi-terms for \( i = 2, 3, \ldots, 14 \).

\( \Pi_{d1} \) Seedling force number, \( f_1 d^3/C_1 J_1 E_1^2 m_1^2 = \phi_1 (\Pi_2, \Pi_3, \Pi_4, \Pi_5, \Pi_7) \)

\( \Pi_{d2} \) Dependent pi-term for critical time, \( \left(t_c / t_g\right) = \phi_2 (\Pi_2, \Pi_3, \Pi_4, \Pi_6) \)

\( \Pi_{d3} \) Bending stress parameter in X-direction, \( (\sigma_{xx} h^2/P) = \phi_3 (\Pi_8, \Pi_9, \ldots, \Pi_{14}) \)

\( \Pi_{d4} \) Bending stress parameter in Y-direction, \( (\sigma_{yy} h^2/P) = \phi_4 (\Pi_8, \Pi_9, \ldots, \Pi_{14}) \)

\( \Pi_{d5} \) Shear stress parameter in X-Y plane, \( (\tau_{xy} h^2/P) = \phi_5 (\Pi_8, \Pi_9, \ldots, \Pi_{14}) \)

\( \Pi_{d1j} \) Value of \( \Pi_{dj} \) when \( \Pi_1 \) is varied, for \( j = 1, 2, 3, 4, 5 \) and \( i = 2, 3, \ldots, 14 \)

\( \Pi_2 \) Environmental temperature index, \( = (\theta_a - \theta_L)/(\theta_H - \theta_L) \)

\( \Pi_3 \) Seed moisture, \( \% d_1 = X_1 \)

\( \Pi_4 \) Soil moisture, \( \% d_2 = Y_1 \)

\( \Pi_5 \) Time index, \( = t/t_c \)

\( \Pi_6 \) Index of ratio of soil impedance to the initial internal energy in the seed, \( = C_1 d^3/J_1 E_1 m_1 \)

(xlii)
\[ \Pi_7 \] Index of ratio of workdone by seedling against gravity restraint to the product of initial stored energy and the soil impedance, \( = G^3 m_1 / J_1 E_1^2 C_1 \). The effect of \( \Pi_7 \) was neglected.

\[ \Pi_8 \] Ratio of seed spacing down the row to hypocotyl radius, \( = b/c \)

\[ \Pi_9 \] Ratio of seed spacing down the row to row spacing, \( = b/a \)

\[ \Pi_{10} \] Ratio of seed spacing down the row to crust thickness, \( = b/h \)

\[ \Pi_{11} \] Position coordinate in X - direction, \( = x/a \)

\[ \Pi_{12} \] Position coordinate in Y - direction, \( = y/a \)

\[ \Pi_{13} \] Poisson's ratio of soil crust, \( = V = e_t / e_a \)

\[ \Pi_{14} \] Index of ratio of sub-soil reaction modulus to the modulus of elasticity of soil crust, \( = k_1 b / E_c \).

\[ d_h \] Hypocotyl diameter of soybean seedling, m

\[ X, Y, Z \] Cartesian coordinates

\[ V \] Poisson's ratio of soil crust.
CHAPTER 1
INTRODUCTION

In order for a farmer to obtain a desired crop stand, he must plant seed of known germination percentage and obtain a predicted percentage of emergence. Seeds of known germination potential are available, yet seedling emergence is a factor that varies widely with soil properties and seedling environmental factors. Seedling emergence is inhibited largely by the occurrence of surface soil crusts (39,145,179,198)* that can form naturally in medium-textured soils due to weather conditions such as rainfall impact and intensity followed by surface air movement and solar radiation causing drying (145,146).

Generally the soils which have low organic matter content (86), high silt and clay proportions, and monovalent cations exhibit the greatest tendencies to form soil crusts (39). Seedling emergence and root development can also be hindered by excessive soil compaction and high bulk density (20,23,58,95,162,192,193,198,199,218,219,220,228) which can occur due to frequent passes by heavy field machines (198,228).

Soil crusting is a serious problem on cultivated lands of India (97,98,148,160,224), Israel (110,111,113), Australia (9,10,40,146,147), U.S.A (37,39,198) and many other countries (44,84,107,125,149,210).

Production of crops such as corn (51), cotton (23,37,51,58,148,168, 218 to 220), soybeans (88,100,102,148,227), grain sorghum (102,197), wheat (99,102,130,145,197), cereals (40,107), sugarbeets (128,174,193,215), mustard (97,98), sunflower (97,98), guar (197), and grasses (73,119), and

*Numbers in brackets refer to the appended references.
vegetables such as cucumbers, lettuce (38,85), radishes (108), potatoes (208), pimento (45) and tomatoes (52,61,121) can be adversely affected by failures to obtain good emergence due to soil crusting. For example, loss of both cotyledons of a soybean seedling during or soon after emergence can reduce yields from 8-9% (103).

Soil crusting problems are quite prevalent in Ohio (52,69,87,88,121, 122,215,227). This can be attributed to soil types and related tillage practices. Of the approximately 12 million acres of cropland in the state, about 5 million acres are comprised of silt loams, silt clay loams, clay loams and silty clays (211). Many farmers are still following conventional tillage practices (often over-tilling) and much of the medium-textured soils described above are fall-plowed. Winter-freezing and thawing in the spring result in seedbed soil aggregates which are conducive to the soil crust formation after planting. Mechanical devices, such as the rotary hoe (23,39,98,227), the harrow (97,98,227) and the cultripacker (39), can sometimes reduce the problem if properly used. Another way of overcoming the ill-effects of soil crust is the selection of varieties capable of not only exerting large emergence forces but also achieving the maximum force rapidly (160).

A number of scientists have been seeking solutions to this worldwide problem of seedling emergence through soil crusts using chemicals, various management techniques, etc. (22,24,38,39,44,45,61,84,85,98,107, 108,125,128,135,141,148,157,160,167,173,198,215,227,228). Some have measured the emergence force of seedlings of monocots and dicots (9,10,13, 26,31,39,40,48 to 51,57,65,75 to 77,79,81,86 to 93,150,153,154,161,181 to 184,198,203,222,223). Seedling emergence force of soybean was related
to the seed characteristic and environmental temperature by Goyal, et al., (87, 88, 89). As the soybean seedling has to emerge from the soil surface along with the cotyledons, it requires more force compared to hypogeal plants (26, 198). If the bending stress, developed by emergence force, is greater than the soil crust strength the seedling will emerge through the crust or follow zones of weakness or cracks (40). The seedling force can be changed by seed characteristic factors such as seed size, seed variety and environmental factors, thus helping to increase the percentage of seedling emergence. Soil crust strength can be changed by various management techniques (39).

VandenBerg (214) stated that simultaneous consideration of soil and plant mechanics would permit maximizing plant growth for particular environmental conditions. The state of bending stress on the soil crust surface due to an emerging seedling has not been defined. The punching mode of failure of soil crusts by seedlings, as defined by Taylor, 1971, may be true for weaker crusts only. Stronger crusts appear to fail by bending.

This study is limited to that portion of the germination process which takes place between the time when the primary root emerges from the seed coat and when the cotyledons are first pushed through the soil surface. The process is referred to as seedling emergence (36, 103). In this study, the soybean seedling emergence force and soil crust properties were measured. Bending stresses generated in soil crusts by emerging dicot seedling were analytically predicted using thin plate theory (209) and dimensional analysis (156). Thermal stresses which cause shrinkage cracks were not considered. Analytically predicted stresses were not verified experimentally...
because of limitation of time available to complete Ph.D dissertation.

In consultation with Dr. N.W. Hopper and Professor S.W. Bone, Department of Agronomy, The Ohio State University, the Williams variety of soybean and a crosby silt loam soil were selected for this study.
CHAPTER 2

OBJECTIVES

The overall objective of this study was to analytically predict the stresses generated in soil crusts by emerging dicot seedlings. The specific objectives were:

1. Develop analytical equations to predict the state of surface stresses generated in soil crusts by emerging soybean seedlings using thin plate theory and dimensional analysis.

2. Experimentally establish the relationship for soybean (Williams variety) seedling emergence force, moisture indices and seed characteristic factors and develop generalized prediction equations for soybean seedling emergence force.

3. Evaluate the effect of environmental temperature and soil impedance on soybean seedling hypocotyl diameter.

4. Evaluate the mechanical properties of a selected soil crust such as Poisson's ratio, modulus of elasticity, bulk density, thickness, and sub-soil reaction modulus and modulus of rupture.

5. Suggest management techniques in crusted soils based upon these studies.
CHAPTER 3
REVIEW OF LITERATURE

3.1 Seedling emergence process

Germination of a soybean seed is the initiation of a marked swelling of a seed followed by rupturing of the seed coat. The primary root develops from the lower end of the hypocotyl and is the first structure to make contact with the soil. As the primary root grows downward in the soil, lateral roots and root hairs develop. The hypocotyl then elongates rapidly, pushing the cotyledons upward out of the soil into the air where these separate into approximately horizontal positions on both sides of the plumule (Figure 1). The plumule then begins active growth, giving rise to the stem and foliage leaves. Cotyledons act as food storage factories until the leaves develop. Emergence is complete at this stage (103). Lateral anchorage is extremely important for the shoot to exert its potentially available force (50). If a zone of low soil strength is present immediately below a high strength layer, the shoot will tend to grow horizontally rather than vertically (9, 10, 40).

The effect of temperature on seedling emergence has been studied by many authors. Martin (142) while working on Calland, Wayne, Wells and Williams varieties of soybean found that the number of hours to reach 50 percent emergence tended to decrease as the temperature increased from 10 to 35°C. The same results are reported by Overholt (159) for Amsoy 71, Chippewa 64, and Wayne cultivars at the temperature range of
(1). Embryo

SEED ANATOMY (Soybean)

Epidermal layer
Hypodermis layer
Inner parenchyma

Seed coat
Endosperm remains

(1). Cuticle, (2). Palisade cells, (3). Intercellular space

SECTION A-A (Cross-section of seed coat)

Cotyledons
Hypocotyl
Root hair
Roots (Primary root)
Lateral root

PARTS OF SEEDLING

Figure 1. Schematic diagram of soybean seed (Mitchell, 1970).
10 to 30°C. The optimum temperature for the root and hypocotyl elongation of cotton during the first four days is reported to be 27° and 33°C respectively by Arndt (8). Grabe and Metzer (94) reported strong inhibition of hypocotyl elongation of soybeans (Ford cultivar) at 25°C and the same emergence rate at 26°C for Hawkeye, Ford and Chippewa cultivars of soybean. According to Gillman (83), inhibition of hypocotyl elongation (Amsoy) occurred between 21-28°C and was a maximum at 25°C. Hatfield and Egli (104) concluded that the rate of hypocotyl elongation of soybean (Cutler, Lee 68) increased rapidly as temperature increased from 10° to 25°C and then rapidly decreased when the temperature was allowed to vary from 30° to 40°C. At 10°C the rate of elongation was very slow and at 40°C germination and elongation did not occur. They suggested a soil temperature of 25-35°C in order to get rapid emergence.

3.2. Seedling emergence force and critical time

Workers involved in emergence force studies used strain gages bonded either on a cantilever beam (13, 153, 154, 161, 184) or on an aluminum ring transducer (51, 52, 75, 76, 77, 79, 86, 89, 90, 91, 93) in a Wheatstone bridge electrical configuration. The findings on maximum seedling emergence force and critical time obtained during 1950-78 by different workers for different types of seeds are summarized in Table 1.

Williams (222, 223) found emergence force and initial seed mass to be closely related (R² = 0.99). He also indicated that 70 percent of variation in emergence force among the species could be accounted for by the amount of hydrolyzable carbohydrate reserve within the seeds.
<table>
<thead>
<tr>
<th>Crop</th>
<th>Force, Critical time, Investigators (Year)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alfalfa</td>
<td>0.15 - Williams (1953)</td>
<td></td>
</tr>
<tr>
<td>Alfalfa</td>
<td>0.18 - Williams (1953)</td>
<td></td>
</tr>
<tr>
<td>Alfalfa</td>
<td>0.19 - Williams (1963)</td>
<td></td>
</tr>
<tr>
<td>Field Peas</td>
<td>0.14 - 48 Jensen, et. al. (1972)</td>
<td>Var. Ranger</td>
</tr>
<tr>
<td>Alkalai Clover</td>
<td>0.09 - 48 Jensen, et. al. (1972)</td>
<td></td>
</tr>
<tr>
<td>Corn</td>
<td>2.67 - Drew, et. al. (1966)</td>
<td></td>
</tr>
<tr>
<td>Corn (Var. Dixie)</td>
<td>2.93 - Drew, et. al. (1965)</td>
<td>Seed size, 0.32 gm/seed</td>
</tr>
<tr>
<td>Corn</td>
<td>2.37 - Drew, et. al. (1965)</td>
<td>Seed size, 0.23 gm/seed</td>
</tr>
<tr>
<td>Corn</td>
<td>1.12 - 130 Niles, et. al. (1969)</td>
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<tr>
<td>Corn</td>
<td>2.46 - Gifford, et. al. (1969)</td>
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<tr>
<td>Corn</td>
<td>0.74 - Parler, et. al. (1975)</td>
<td>Planting depth Bulk density 2 cm 1.43 gm/cm³</td>
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<tr>
<td>Corn</td>
<td>0.96 - Parler, et. al. (1975)</td>
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<tr>
<td>Corn</td>
<td>1.19 - Parler, et. al. (1975)</td>
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<td>Corn</td>
<td>0.65 - Parler, et. al. (1975)</td>
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<tr>
<td>Corn</td>
<td>0.98 - Parler, et. al. (1975)</td>
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<tr>
<td>Corn</td>
<td>0.06 - Parler, et. al. (1975)</td>
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<tr>
<td>Badharia, et. al. (1977)</td>
<td>0.98 - Badharia, et. al. (1977)</td>
<td>Var. Vilay Composite</td>
</tr>
<tr>
<td>Cotton</td>
<td>0.25 - 36 Badharia, et. al. (1977)</td>
<td>Var. VL 56</td>
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<tr>
<td>Cotton</td>
<td>0.26 - 51 Badharia, et. al. (1977)</td>
<td>Var. Local</td>
</tr>
<tr>
<td>Cotton</td>
<td>2.22 - Drew, et. al. (1955)</td>
<td>Var. Auburn - 56</td>
</tr>
<tr>
<td>Cotton</td>
<td>1.59 - 70 Garner, Bowen (1966)</td>
<td>32%, soil moisture:7.8%</td>
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<td>Cotton</td>
<td>2.07 - 50 Garner, Bowen (1966)</td>
<td>32%, soil moisture:6.7%</td>
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<td>5.80 - Edwards (1966)</td>
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<td>8.50 - Edwards (1966)</td>
<td>Two seeds</td>
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<tr>
<td>Cotton</td>
<td>0.59 - Edwards (1966)</td>
<td>Three seeds</td>
</tr>
<tr>
<td>Cotton</td>
<td>2.59 - Gifford, Thran (1969)</td>
<td></td>
</tr>
<tr>
<td>Cotton (Calculated)</td>
<td>7.82 - Drew, et. al. (1971)</td>
<td>Seed dia Axial pressure 1.25 mm 2.5 atm</td>
</tr>
<tr>
<td>Cotton</td>
<td>3.02 - Drew, et. al. (1971)</td>
<td>1.23 mm 12.5 atm</td>
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<td>Cotton</td>
<td>4.63 - Drew, et. al. (1971)</td>
<td>1.73 mm 15.0 atm</td>
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<tr>
<td>Cotton</td>
<td>2.70 - Drew, et. al. (1971)</td>
<td>Temperature: 20-24°C</td>
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<td>2.45 - Drew, et. al. (1971)</td>
<td>Temperature: 25.40°C</td>
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<tr>
<td>Cotton</td>
<td>2.58 - Drew, et. al. (1971)</td>
<td>Temperature: 32.2°C</td>
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<tr>
<td>Cotton</td>
<td>2.22 - Drew, et. al. (1971)</td>
<td>Temperature: 25.7°C</td>
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<tr>
<td>Crimson Clover</td>
<td>0.23 - Williams (1956)</td>
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<td>0.22 - Williams (1956)</td>
<td>Var. Auburn</td>
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<td>Crimson Clover</td>
<td>0.24 - Williams (1956)</td>
<td>Var. Talladega</td>
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<td>Var. Dixie</td>
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<td>Var. Common</td>
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<td>0.37 - Williams (1956)</td>
<td>Var. Kentucky, sel.</td>
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<td>Crimson Clover</td>
<td>0.51 - Williams (1956)</td>
<td>Var. Antelope</td>
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<tr>
<td>Crimson Clover</td>
<td>0.62 - Williams (1963)</td>
<td>Var. Mississippi, sel.</td>
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<table>
<thead>
<tr>
<th>Crop</th>
<th>Force, Critical time, Investigators (Year)</th>
<th>Remarks</th>
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<tbody>
<tr>
<td>Cucumber</td>
<td>1.57 - Gifford, Thran (1969)</td>
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<td>Lino Beans</td>
<td>3.06 - Gifford, Thran (1969)</td>
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<tr>
<td>Mechanical seedling</td>
<td>3.60 - Buchele, et. al. (1967)</td>
<td>Predicted</td>
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<td>Mechanical seedling</td>
<td>3.17 - Buchele, et. al. (1967)</td>
<td>Measured</td>
</tr>
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<td>Mechanical seedling</td>
<td>0.62 - Morton, Buchele (1960)</td>
<td>Tip dia. Surface compaction 0.269 cm 0.5 psi</td>
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<tr>
<td>Mechanical seedling</td>
<td>2.49 - Morton, Buchele (1960)</td>
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<tr>
<td>Mechanical seedling</td>
<td>4.18 - Morton, Buchele (1960)</td>
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<tr>
<td>Narrowleaf Bush foot trefoil</td>
<td>0.05 - 144 Jensen, et. al. (1972)</td>
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<tr>
<td>Red Clover</td>
<td>0.12 - 48 Jensen, et. al. (1972)</td>
<td>Var. Kentland</td>
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<tr>
<td>Red Clover</td>
<td>0.16 - Williams (1956)</td>
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<td>Rose Clover</td>
<td>0.26 - Williams (1956)</td>
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<tr>
<td>Soybean</td>
<td>2.64 - 107 Goyal (1977)</td>
<td>Temp. 5.0°C, soil Compaction 0.25 kgf/sq.cm</td>
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<tr>
<td>Strawberry</td>
<td>0.11 - 30 Jensen, et. al. (1972)</td>
<td>Var. Satina</td>
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<td>Sunflower</td>
<td>0.59 - Williams (1956)</td>
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</tr>
<tr>
<td>Sunflower</td>
<td>0.06 - Gifford, Thran (1969)</td>
<td></td>
</tr>
<tr>
<td>Tall Wheat-grass</td>
<td>0.12 - 144 Jensen, et. al. (1972)</td>
<td></td>
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</table>
Drew and Buchele (49) & Williams (223) measured the emergence force of monocots by a method in which the seedling was allowed to grow in vermiculite and to develop its force against a glass rod in a vertical glass tube. Gifford and Thran (79) found positive correlation between seed size and emergence force. Miles and Matthes (150) used a linearly variable differential transformer to measure the deflection of cantilever beam due to force exerted by corn seedling. Esashi and Leopold (65) measured physical forces in germination of Xanthium seeds by U-tube device which had rubber stop at one end to hold the seed and a strength meter at the other end.

Jensen, Frelich and Gifford (127) concluded that seedling force differed significantly for various forage species and was positively correlated with seed mass \( r = 0.97 \). They also indicated that the seedling vigor is determined by how fast a seedling is able to exert its force. Parihar and Aggarwal (161) found that corn seed size and depth of planting had no effect on the corn seedling force.

Badhoria, Aggarwal and Tripathi (13) observed no significant differences in emergence force of three corn varieties, i.e., Vijay Composite, VL34 and Local. They also indicated that probability of emergence was high if seedling was able to exert its force earlier. Vijay Composite had higher probability of emerging through soil crust than other corn varieties.

Taylor and Ratliff (203) measured the root growth force using strain gage force transducer. The root growth force was in the range of 0.2 to 2.0N, 0.5 to 3.4N, 1.6 to 5.1N for cotton, peas and peanuts respectively. The average critical time was 14, 17 and 79 hours for cotton, peas and peanuts respectively. Stolzy and Barley (190) found root growth pressure for peanut as 6.1 bars.
3.3 Soil crust formation and its effects

Crusts are those hard layers that develop at the soil surface due to the action of rain drop or irrigation water and subsequent drying. The structure of this layer is markedly different from that of the soil mass below (134). McIntyre (147) reported that the soil crusts formed by rainfall impact consisted of a 0.1 mm skin and a 1.5 mm thick washed-in region. Thin structures from uncrusted soil showed an open structure with a large volume of pores. On crusting, the particles became densely packed with negligible air spaces (39). In short, the crust has higher bulk density (20, 21, 22, 23, 39, 63, 100, 113, 121, 122, 137, 138, 224), lower macro-porosity and higher mechanical strength than the underlying soil (39, 122, 138, 140, 195).

The soil crust is formed (Figure 2) as a result of (i) mechanical destruction of aggregates and simultaneous compaction by rain drop impact, (ii) Washing of fine particles into the inter-aggregate spaces and (iii) rupture of soil aggregates by air entrapped in the previously dry soil particles (147, 195). Tackett and Pearson (195) presented clear evidence of particle segregation under simulated rainfall and of a marked increase in density of a very thin surface layer. This densification is attributed to the following factors (111): (a) Tendency of platy particles in a state of semi-suspension to settle with their long axis horizontally, (b) Possible attraction between adjoining particles.

The strength of the crust on any particular soil is a result of the complex physical and physico-chemical processes or reactions which are controlled by the proportion and nature of the soil components and by external conditions. Different soils respond differently to the environmental conditions to which they are subjected (39).
Instantaneous slaking of soil aggregates.
2 Dispersion and orientation of finer particles.
3 Results in zone of higher bulk density at surface.
4 Soil dries.
5 Surface tension forces cause particle interaction and orientation as shrinkage takes place. Surface forces interact on drying and create greater soil strength and hard layer is formed.

Structure in Top Few mm of Soils
i) It has few large pores.
ii) High bulk density.
iii) Characterized by platiness, stratification, orientation of different sized materials.
iv) It is harder than underlying soil.
v) Has low saturated hydraulic conductivity and limits infiltration.
vi) Prevents emergence of seedlings.

FIGURE 2. Process of Crust Formation
Probably the most important direct effect of soil crusts is on seedling emergence and early development of seedlings. Their influence in decreasing or preventing emergence has been illustrated many times. Also seedlings may be injured by movement of soil during cultivation of a crusted soil (39). The energy of the seedlings and soil crust impedance decide the fate of a seedling. If the energy in the seedling falls short of soil crust impedance, seedling cannot push through the crust and the result is a poor crop stand.

Other important effects of soil crusts include reduction in water infiltration, increased runoff and erosion, reduced water-use efficiency, restriction of air capacity and internal aeration, decreased microbial activity and increased surface soil impedance (39).

3.4 Simulated models for soil crusts and seedling emergence

Taylor (197) evaluated emergence of wheat, grain sorghum, and guar through nonporous wax surface crusts (200,201) with wax penetration numbers (12) ranging from 15 to 20 and with thicknesses of 0.625, 1.25, 2.5 cm. He found that emergence was affected by hardness and thickness of crusts. Ten to twenty percent of the cotyledon leaves and growing tips were sheared from the guar seedlings by harder wax crusts. The hypocotyl broke at the juncture of the cotyledons and the hypocotyl. These crusts do not represent true soil crusts as the wax crusts are not brittle and are temperature dependent. The mechanical probe has been used by many investigators (9,42,63,96,153,154,182,190,192) to simulate the actual seedling without understanding the difference in properties of both. A definitive simulation study should include all the pertinent properties of the soil-seed system in a study of the behaviour of seedlings from the results on a mechanical seedling.
3.5 Failure mechanisms of crusted soils during seedling emergence

Taylor (197) indicated that seedlings emerge through surface crusts by at least four mechanisms: (a) The seedlings often can exert sufficient pressure to displace soil material and create a path for an individual seedling. The hardness of crust determines the percentage of seedlings which can emerge by this mechanism. (b) A group of seedlings may exert sufficient total force to rupture and lift a portion of the crust. Through this mechanism, a group of seedlings exerting force on a small area of surface crust may have the ability to emerge through a crust which would prevent emergence of an individual plant. (c) Individual seedling may emerge through cracks or ruptures which have developed as a result of internal stresses in the crusts (40). (d) Some of the individual seedlings, such as wheat and grain sorghum, transfer water from roots to the shoot tip entrapped in the crust. This accumulation of guttated water can change the shear strength of a soil crust.

Hanks (100) mentioned that wheat seedlings do not press on the crust until broken but rather worm their way slowly through the crust. Based on this he assumed that modulus of rupture (171) was a good measure of crust strength.

Hadas and Stibbe (99) observed that the deeper the wheat seed was placed, the harder the soil crust became when reached by the coleoptile, and the chance of a coleoptile breaking through it was poor.

Arndt (9) concluded that in the absence of a seal (crust), seedlings emerged by weaving their way through voids and by displacing or deforming some soil obstructions. Under sealed conditions, the resistance at the surface is such that buckling often proceeds in the horizontal direction with no emergence. The mechanics of seedling emergence in the presence of
surface crusts change with water content of crust mechanical composition of soil, frequency of cracking, size of the seedling, location of the seedling in the vertical plane, and location of the seedling in the horizontal plane particularly w.r.t positions of the natural cracks in the seal. He presented 6 broad classifications of impedance mechanisms (Figure 3) based on crust cracking characteristics and seedling size:

(a) Adequate cracking for fine seedlings which are flexible with relatively ineffective lifting force. Here the cracks are sufficiently frequent and wide to permit free emergence of most of the seedlings either directly or by reasonable detours, (b) Adequate cracking for coarse seedlings which are rigid with relatively effective lifting force. Here strength of small plates is immaterial, (c) Inadequate cracking for fine seedlings causes delayed and partial emergence of sown crops by detouring. In case of self-sown annuals, the plates are lifted bodily without tilting and jamming on neighbouring plates since the combined effort is sufficient to overcome the gravitational force of the plate, (d) Inadequate cracking for free emergence of coarse seedlings. Here jamming situation arises which seedling may or may not overcome, (e) Absence of cracks for fine seedlings. Since the individual seedlings have little lifting power, they cannot emerge unless the seal is very wet, or the stand is dense enough for the combined effort to produce shear failure of the seal. (f) Absence of cracks for coarse seedlings. The seal is held rigid over the seedling by its wide extent. The displaced cone may be small and remain intact, or it may be large with secondary ruptures which are probably caused by tension in the upper surface due to the weight of cone over the point of lift. This secondary failure
Figure 3. The main combinations of seedling size and crust cracking characteristics used in the identification of failure mechanisms (Arndt, 1965a).
was similar to the condition of loading in the Richards' apparatus (171). In general, for fine seedlings frequency of cracking was most effective whereas both size and frequency of cracking were significant for coarse seedlings.

Assur (11) mentioned punching of crusted sheets (salt ice) due to highly concentrated loads.

Taylor (198), while reviewing the work of others, mentioned that emerging seedlings, with a shoot about 1mm or less in diameter (grasses and cereals), usually displace soil particles by compression and shear until the tip is near the soil surface. At that time, if the force transmitted by the tip is sufficient to overcome the tensile strength of soil crust, an inverted cone of soil is ruptured out of the crust. Seedlings of dicotyledonous crops emerge by rupturing the soil crust in a dome or cone large enough to accommodate the cotyledons.

These failure mechanisms, mentioned above, may be true for weaker crusts and not for stronger crusts. It is hypothesized that stronger crusts appear to fail in bending during seedling emergence. Therefore theory of thin plates can be successfully applied to soil crusts supported by columns (seedlings) to get stress conditions on the soil crust surface.
CHAPTER 4

THEORETICAL ANALYSIS OF SURFACE STRESSES GENERATED IN
SOIL CRUSTS BY EMERGING DICOT SEEDLINGS

4.1 Introduction

VandenBerg (214) stated that simultaneous consideration of soil and plant mechanics would permit maximizing plant growth for particular environmental conditions. The state of bending stress on the soil crust surface due to an emerging seedling has not been defined. The assumption in this study is that emergence through a crusted soil would occur if the maximum bending stress on the soil crust surface generated by an emerging seedling is greater than the modulus of rupture of the soil crust.

The force which the shoots of grasses and cereals (monocots) exert on soil crusts is a concentrated point load. Stresses at that point are relatively large. In the case of dicotyledonous crops such as cotton, peanuts, and soybeans (epigeal plants), the cotyledons are pushed or pulled through the soil crust and the seedling force is distributed over a small area instead of being a point load (198). If the maximum stress generated due to this force is greater than the modulus of rupture of soil crust, the seedling will emerge through the crust or follow a zone of weakness or cracks.

The soil crust is characterized by a plate-like structure (39). Physically it can be thought of as a thin plate supported by rows of seedlings and under-laid by un-crusted soil which has properties different from those of the soil crust. The physical system is schematically presented
in Figure 4. The following assumptions were made: (a) The soil crust is an infinite plate resting on an elastic subgrade, (b) The soil medium is elastic and isotropic, (c) The crust (plate) thickness is small compared to plate dimensions (Figure 4), (d) The plate is large in relation to seedling spacing (row spacing and seedling spacing down the row), (e) All seedlings exert equal force, (f) The load is uniformly distributed over a circle of radius c, (g) The seedling dimensions are small compared to plate dimensions, and (h) The plate is thin and flat, and unbroken.

To compute bending stresses generated in the soil crust by emerging dicot seedling, Navier's double series solution (209) was applied. This solution gives the deflection of the plate due to a load P distributed over a square of side u. It was therefore assumed that the side of the equivalent square was given by the relation: \( u^2 = \Pi c^2 \).

4.2 Governing equations

\[
\frac{4}{3} \frac{\partial^4 w}{\partial x^4} + 2 \frac{4}{3} \frac{\partial^4 w}{\partial x^2 \partial y^2} + \frac{4}{3} \frac{\partial^4 w}{\partial y^4} = \frac{q}{D} - \frac{k_1 w}{D}
\]

\( \sigma_{xx} = -\frac{E_c}{(1-v^2)} \left\{ \frac{\partial^2 w}{\partial x^2} + v \frac{\partial^2 w}{\partial y^2} \right\} \)

\( \sigma_{yy} = -\frac{E_c}{(1-v^2)} \left\{ \frac{\partial^2 w}{\partial y^2} + v \frac{\partial^2 w}{\partial x^2} \right\} \)
Figure 4. Dicot seedling and soil-crust system.
\[ \sigma_{xy} = \frac{-E_c z}{(1+W)} \left\{ \frac{2w}{a \times a \times Y} \right\} \]

\[ D = \frac{E_c h^3}{12(1-V^2)} \]

\[ w = \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} A_{mn} \left\{ \cos \left( \frac{2mn \pi x}{a} \right) \right\} \left\{ \cos \left( \frac{2nm \pi y}{b} \right) \right\} \]

\[ q = \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} a_{mn} \left\{ \cos \left( \frac{2mn \pi x}{a} \right) \right\} \left\{ \cos \left( \frac{2nm \pi y}{b} \right) \right\} \]

\[ = \frac{p}{\pi c^2} = \frac{p}{u^2} \quad \text{for} \quad -\frac{u}{2} \leq x \leq +\frac{u}{2}, -\frac{u}{2} \leq y \leq +\frac{u}{2} \]

\[ = 0 \quad \text{elsewhere} \]

The boundary conditions are:

\[ \frac{\partial w}{\partial x} = 0 \quad \text{at} \quad x = \pm \frac{a}{2}, y = \pm \frac{b}{2} \]

\[ \frac{\partial w}{\partial y} = 0 \quad \text{at} \quad x = \pm \frac{a}{2}, y = \pm \frac{b}{2} \]

\[ D \frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} = 0 \quad \text{at} \quad x = \pm \frac{a}{2}, y = \pm \frac{b}{2} \]

4.3 Stress analysis

From equations 4.1, 4.6, and 4.7 one obtains

\[ A_{mn} = \frac{a_{mn}}{D \Pi \left\{ \left( \frac{m^2}{a^2} + \frac{n^2}{b^2} \right) \right\}^2 + k_1} \]

\[ \text{From equation 4.7} \]

\[ A_{mn} = \frac{4p}{\mu_{mn}^2 \Pi^2} \left\{ \sin \left( \frac{mn \pi u}{a} \right) \sin \left( \frac{mn \pi u}{b} \right) \right\} \quad \text{for} \quad m, n \neq 0 \]

\[ = \frac{4p}{a \mu n} \left\{ \sin \left( \frac{mn \pi u}{b} \right) \right\} \quad \text{for} \quad m = 0, n \neq 0 \]

\[ = \frac{4p}{b \mu m} \left\{ \sin \left( \frac{mn \pi u}{a} \right) \right\} \quad \text{for} \quad m \neq 0, n = 0 \]
\[ w = \frac{-4P}{ab} k_1 \sum_{n=1}^{\infty} \left\{ \frac{4P}{4\pi n^2} \sin \left( \frac{n\pi u}{b} \right) \cos \left( \frac{2nmx}{a} \right) \right\} \frac{1}{4 \pi n^2 + k_1} \]

\[ - \sum_{m=1}^{\infty} \left\{ \frac{4P}{4\pi m^2} \sin \left( \frac{m\pi u}{a} \right) \cos \left( \frac{2mny}{b} \right) \right\} \frac{1}{4 \pi m^2 + k_1} \]

\[ \frac{4P}{mn^2} \sum_{m=1}^{\infty} \left\{ \frac{\sin \left( \frac{m\pi u}{a} \right) \sin \left( \frac{n\pi u}{b} \right)}{a^2 + b^2} \right\} \left\{ \frac{\cos \left( \frac{2mny}{a} \right) \cos \left( \frac{2n\pi y}{b} \right)}{a^2 + b^2} \right\} \frac{4\pi n}{\pi^2} \left\{ \sum_{n=1}^{\infty} \frac{1}{4 \pi n^2 + k_1} \right\} \]

\[ \begin{align*}
\pi_4 &= + \left\{ \frac{96\sqrt{\pi}}{1} \cdot \frac{\pi_8}{2} \sum_{m=1}^{\infty} \frac{\sin \left( \frac{m\pi}{\pi_9} \frac{m}{\pi_9} \right)}{a^2 + b^2} \right\} \\
&\quad + \left\{ \frac{96\sqrt{\pi}}{\pi_8 \pi_9} \sum_{n=1}^{\infty} \frac{\pi_4 n^4 + 12 \left( \pi_9 \pi_10 / \pi_9 \right) \left( 1 - \pi_9^2 \right)}{\pi_10} \right\} \\
&\quad + \left\{ \frac{384 \pi_8}{\pi_9} \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \frac{\pi_2 \pi_9 m/n + n/m}{a^2 + b^2} \right\} \\
&\quad \left\{ \pi_2 \pi_9 m^2 + n^2 + 12 \left( \pi_9 \pi_10 / \pi_9 \right) \left( 1 - \pi_9^2 \right) \pi_10 \right\} \\
&\quad \left\{ \pi_4 \left( \pi_2 m^2 + n^2 \right)^2 + 12 \left( \pi_9 \pi_10 / \pi_9 \right) \left( 1 - \pi_9^2 \right) \right\} \right\} \right\} \]

Using the pi-terms given in Table 2 and introducing

\[ u^2 = \pi_0 \pi_2 \]

along with \( \pi = -n/2 \), equations 4.2 to 4.8 and 4.14 gave the following non-dimensional relationships:

\[ \pi_{d4} = \]

\[ \begin{align*}
\pi_{d4} &= + \left\{ \frac{96\sqrt{\pi}}{1} \cdot \frac{\pi_8}{2} \sum_{m=1}^{\infty} \frac{\sin \left( \frac{m\pi}{\pi_9} \frac{m}{\pi_9} \right)}{a^2 + b^2} \right\} \\
&\quad + \left\{ \frac{96\sqrt{\pi}}{\pi_8 \pi_9} \sum_{n=1}^{\infty} \frac{\pi_4 n^4 + 12 \left( \pi_9 \pi_10 / \pi_9 \right) \left( 1 - \pi_9^2 \right)}{\pi_10} \right\} \\
&\quad + \left\{ \frac{384 \pi_8}{\pi_9} \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \frac{\pi_2 \pi_9 m/n + n/m}{a^2 + b^2} \right\} \\
&\quad \left\{ \pi_2 \pi_9 m^2 + n^2 + 12 \left( \pi_9 \pi_10 / \pi_9 \right) \left( 1 - \pi_9^2 \right) \pi_10 \right\} \\
&\quad \left\{ \pi_4 \left( \pi_2 m^2 + n^2 \right)^2 + 12 \left( \pi_9 \pi_10 / \pi_9 \right) \left( 1 - \pi_9^2 \right) \right\} \right\} \right\} \right\} \]

\[ \begin{align*}
\pi_{d4} &= + \left\{ \frac{96\sqrt{\pi}}{1} \cdot \frac{\pi_8}{2} \sum_{m=1}^{\infty} \frac{\sin \left( \frac{m\pi}{\pi_9} \frac{m}{\pi_9} \right)}{a^2 + b^2} \right\} \\
&\quad + \left\{ \frac{96\sqrt{\pi}}{\pi_8 \pi_9} \sum_{n=1}^{\infty} \frac{\pi_4 n^4 + 12 \left( \pi_9 \pi_10 / \pi_9 \right) \left( 1 - \pi_9^2 \right)}{\pi_10} \right\} \\
&\quad + \left\{ \frac{384 \pi_8}{\pi_9} \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \frac{\pi_2 \pi_9 m/n + n/m}{a^2 + b^2} \right\} \\
&\quad \left\{ \pi_2 \pi_9 m^2 + n^2 + 12 \left( \pi_9 \pi_10 / \pi_9 \right) \left( 1 - \pi_9^2 \right) \pi_10 \right\} \\
&\quad \left\{ \pi_4 \left( \pi_2 m^2 + n^2 \right)^2 + 12 \left( \pi_9 \pi_10 / \pi_9 \right) \left( 1 - \pi_9^2 \right) \right\} \right\} \right\} \right\}}
Table 2. Pi-terms for stresses generated in soil crusts by emerging dicot seedlings.

<table>
<thead>
<tr>
<th>Pi-term</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi_{d3}$ = $\left(\sigma_{x}xh^2\right)/P$</td>
<td>Crust surface bending stress number in x-direction.</td>
</tr>
<tr>
<td>$\pi_{d4}$ = $\left(\sigma_{yy}y^2\right)/P$</td>
<td>Crust surface bending stress number in Y-direction.</td>
</tr>
<tr>
<td>$\pi_{d5}$ = $\left(\sigma_{xy}y^2\right)/P$</td>
<td>Shear stress number in X-Y plane.</td>
</tr>
<tr>
<td>$\pi_{8}$ = $b/c$</td>
<td>Ratio of seed spacing down the row to hypocotyl radius.</td>
</tr>
<tr>
<td>$\pi_{9}$ = $b/a$</td>
<td>Ratio of seed spacing down the row to row spacing.</td>
</tr>
<tr>
<td>$\pi_{10}$ = $b/h$</td>
<td>Ratio of seed spacing down the row to crust thickness.</td>
</tr>
<tr>
<td>$\pi_{11}$ = $x/a$</td>
<td>Position coordinate in x-direction.</td>
</tr>
<tr>
<td>$\pi_{12}$ = $y/b$</td>
<td>Position coordinate in Y-direction.</td>
</tr>
<tr>
<td>$\pi_{13}$ = $V$</td>
<td>Poisson's ratio of soil crust.</td>
</tr>
<tr>
<td>$\pi_{14}$ = $k_{1}b/E_c$</td>
<td>Index of ratio of sub-soil reaction modulus to the modulus of elasticity of soil crust.</td>
</tr>
</tbody>
</table>
\[
\Pi_{d3} = + \left[ \frac{96}{\Pi_9} \cdot \frac{\Pi_8}{2} \right]_m^{\infty} \sum_{n=1}^{\infty} \left\{ m \left( \sin \left( m \frac{1.5}{\Pi_9} \Pi_8 \right) \cos \left( 2m\Pi_{11} \right) \right) \right. \\
\left\{ (n^4m^4 + 12 \left( \Pi_{14m}^{11} \Pi_9 \right) (1-n^2_{13})) \cos \left( n\Pi_{12} \right) \right. \\
\left\{ (n^4n^2 + 12 \left( \Pi_{14n}^{13} \Pi_9 \right) (1-n^2_{13})) \sin \left( n\Pi_{12} \right) \sin \left( n\Pi_{12} \right) \right. \\
\left\{ (n^2m/n + n_12m/m) \left( \sin \left( m\Pi_{11.5} \Pi_9 \right) \sin \left( n\Pi_{11.5} \Pi_9 \right) \right)^* \right. \\
\left( \cos \left( 2m\Pi_{11} \right) \cos \left( 2n\Pi_{12} \right) \right) \right. \\
\left( \Pi_{14n}^{13} \Pi_9^2 + n^2)^2 + 12 \left( \Pi_{14n}^{13} \Pi_9 \right) (1-n^2_{13}) \right. \\
\left. \right) \right] \\
\right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right. \right.
CHAPTER 5

SOYBEAN SEEDLING PROPERTIES AND EMERGENCE FORCE

5.1 Experimental design

Seedling force during emergence through the soil cannot yet be described analytically starting with basic physical governing equations. An alternative approach is to employ dimensional analysis (156) combined with appropriately designed experiments.

This investigation was organized to obtain prediction equations to relate a dependent dimensionless parameter to other dimensionless parameters that characterize the physical system; in this case a seedling emerging and forcing its way to the surface of the soil.

Such a prediction equation to be valid must be based on identification of a complete and non-redundant set of physical quantities pertinent to this system behavior. The Buckingham-Pi-Theorem is then applied to produce a set of independent and dimensionless groups or "pi-terms". Then by appropriate experimental design and analysis, a prediction equation can be produced. This gives the functional, mathematical relationship among the pi-terms that characterize the system. It can be used to analyze how the system responds to changes in the pertinent physical quantities that control system behavior, such as environmental variables. A prediction equation obtained in this way has an important advantage in that it usually has greater generality than one obtainable by other methods. Physical sciences such as fluid dynamics, transport phenomena, solid mechanics and
other physical phenomena, have employed dimensional analysis to describe system behavior. More complex systems, such as this emergence seedling force system are, in my opinion, amenable to analysis based on dimensional considerations and prediction relationships among dimensionless groups, or "pi-terms." A critical requirement is identification of a complete but non-redundant set of the physical quantities that describe the system. A basic hypothesis in this study is that the physical quantities that have been identified and employed are complete and non-redundant.

5.1.1 Selection of physical parameters

Effects of moisture indices and other physical parameters on the seedling force number and the critical time (Time at which seedling attains its maximum force) were evaluated experimentally. The seedling force system and the critical time system are inter-related. Therefore physical parameters were identified for both systems.

Identification of parameters that are pertinent, non-redundant and fully descriptive of the system is the most critical part of any problem using similitude techniques. The basic dimensions used were \( F = \text{force} \), \( M = \text{mass} \), \( L = \text{length} \), \( T = \text{time} \), \( H = \text{heat} \) and \( \Theta = \text{temperature} \). In systems wherein inertial forces are significant, \( F \) and \( M \) are inter-related by Newton's Second Law. In the system involved in this study, inertial forces were assumed to be negligible.

The seedling emergence force \( (f_1) \) and the critical time \( (t_c) \) are dependent variables. The independent parameters believed to be appropriate, based upon previous research, are given in Tables 3 and 4.

Gravity force, \( (G) \) which restrains the seedling's upward growth, is is an independent quantity. Gravitational field strength is defined by the Universal Law of Gravitation - "The force of attraction between two
Table 3. List of physical parameters in the soybean seedling emergence force system.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
<th>Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f_1 )</td>
<td>Seedling emergence force per seedling.</td>
<td>Newton</td>
<td>F</td>
</tr>
<tr>
<td>G</td>
<td>Gravitational field strength.</td>
<td>Newton/kilogram</td>
<td>FM(^{-1})</td>
</tr>
<tr>
<td>( E_1 )</td>
<td>Internal energy of the seed.</td>
<td>Joules/kilogram</td>
<td>HM(^{-1})</td>
</tr>
<tr>
<td>( m_1 )</td>
<td>Initial seed mass.</td>
<td>Kilogram</td>
<td>M</td>
</tr>
<tr>
<td>( J_1 )</td>
<td>Mechanical equivalent of heat.</td>
<td>Newton-meter/Joule</td>
<td>FLH(^{-1})</td>
</tr>
<tr>
<td>( X_1 )</td>
<td>Seed moisture, db</td>
<td>%</td>
<td>-</td>
</tr>
<tr>
<td>( Y_1 )</td>
<td>Soil moisture, db</td>
<td>%</td>
<td>-</td>
</tr>
<tr>
<td>Z</td>
<td>Environmental temperature index.</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>( C_1 )</td>
<td>Soil impedance.</td>
<td>Pascals</td>
<td>FL(^{-2})</td>
</tr>
<tr>
<td>K</td>
<td>Ratio of elapsed time (t) to time at which seedling attains its maximum force, ((t_c)).</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 4. List of physical parameters governing the critical time (Time at which seedling attains its maximum force).

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
<th>Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t_c )</td>
<td>Critical time.</td>
<td>Hours</td>
<td>T</td>
</tr>
<tr>
<td>( E_1 )</td>
<td>Internal energy of the seed.</td>
<td>Joules/kilogram</td>
<td>HM(^{-1})</td>
</tr>
<tr>
<td>( m_1 )</td>
<td>Initial seed mass.</td>
<td>Kilogram</td>
<td>M</td>
</tr>
<tr>
<td>d</td>
<td>Mean seed diameter.</td>
<td>Meter</td>
<td>L</td>
</tr>
<tr>
<td>( J_1 )</td>
<td>Mechanical equivalent of heat.</td>
<td>Newton-meter/Joules</td>
<td>FLH(^{-1})</td>
</tr>
<tr>
<td>( X_1 )</td>
<td>Seed moisture, db</td>
<td>%</td>
<td>-</td>
</tr>
<tr>
<td>( Y_1 )</td>
<td>Soil moisture, db</td>
<td>%</td>
<td>-</td>
</tr>
<tr>
<td>Z</td>
<td>Environmental temperature index.</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>( C_1 )</td>
<td>Soil impedance.</td>
<td>Pascals</td>
<td>FL(^{-2})</td>
</tr>
<tr>
<td>( t_g )</td>
<td>Characteristic time factor of growth. Hours</td>
<td>Hours</td>
<td>T</td>
</tr>
</tbody>
</table>
objects is directly proportional to the product of the masses of the two objects and is inversely proportional to the square of the distance between the two objects". If one of the objects is the earth and \( r_1 \) is the distance between the center of seed mass \( m_1 \) and the center of the earth, then \( G \) is defined as:

\[
G = \left(\frac{k}{(m_1)^2}\right) (r_1^2)
\]

(5.1)

where \( k \) is a constant of proportionality and \( G \) is a measure of gravitational force per unit mass.

The energy expended by the seedling in emerging through the soil is derived from initial stored energy \((E_1)\) in the seed. The energy content of the seed is determined by its mass \((m_1)\). The energy consumed during emergence may amount to the energy equivalent of one-half the dry weight of the seed \((36)\). Mean seed diameter \((d)\), because of its correlation with vigor, influences the critical time \((t_c)\). The effect of seed size on emergence has been studied by several investigators \((32, 33, 36, 142, 159, 166)\).

The mechanical equivalent of heat \((J_1)\) is a basic parameter, as chemical energy is converted into mechanical energy. The chemical energy is in the form of carbohydrates, fats, proteins, and fiber. Energy is required for biological processes like migration of chromosomes, streaming of protoplasm, cell division, cell enlargement and for development of the required thrust to pierce the seed coat. Respiration breaks down the complex food molecules stored in the seed into simpler compounds, liberates carbon dioxide and produces the required energy. The cotyledons are the store houses of this energy, and they supply the nutrients until the foliage leaves develop. The loss in dry weight of seed is used for the growth process and basic metabolism. Additional seed energy is utilized in overcoming mechanical impedance and by fungi or other microflora activity \((109)\).
The loss in seed weight is generally attributed to carbon dioxide formation, heat formation, and the energy expended by the seedling during the emergence process (36).

The seed coat (Figure 1) constitutes a barrier between the seed and the external environment (151). Imbibition followed by rupturing of the seed coat (36) is essential for germination. Moisture (X) is required to hydrate the seed coat and to make it permeable to gas exchange. The critical stage is the soil moisture at the beginning of imbibition. An excess of water limits oxygen availability due to low solubility of oxygen in water. It also limits air and water competition for physical space in the environment of the seed. Taylor (1971) suggested manipulating seed moisture and growth medium moisture (Y) as one of the techniques to improve seedling emergence through the soil crust (in Barnes, 1971). Moisture is also essential for growth processes and maintaining turgor pressure in the cells.

Temperature ($\theta_a$) is an important growth factor and affects the translocation and respiratory activities of the plant. Temperature to which seeds are exposed during imbibition is critical to both the rate of germination and the final germination percentage (36). Optimum temperature is the temperature at which the growth rate is maximum. Extrapolation of growth curves to lower and higher temperatures provides minimum and maximum temperature values beyond which growth cannot occur. Minimum, optimum and maximum temperatures are referred to as cardinal temperatures. The maximum and minimum values provide the climatic range over which a crop may be expected to survive. Low temperatures not only reduce percentage germination but also delay emergence. Low temperatures slow down cell activity and decrease gas diffusion. Temperatures above optimum increase the rate of respiration in the cells of developing seedlings and decrease
the rate of enzymatic action. Ambient temperatures also affect turgor (tissue) pressure during the emergence process. For these reasons, temperature affects the rate and percentage of emergence. Henry (1969) indicated that higher temperatures caused a low seed-use efficiency but high growth. He mentions potential danger of exhausting seed reserves before emergence when seed is highly stressed. Critical values were defined as the temperatures below and above which emergence is less than 50 percent. These were taken as 5°C and 45°C for soybeans (43,118).

The degree of soil compaction ($C_t$), which results in high bulk density, might reduce growth in several ways such as by restricted moisture availability, increased mechanical impedance, restricted oxygen supply, restricted supply of nutrients, and reduction of soil pore size. An increase in soil compaction can reduce crop yield (a) by reducing root proliferation, depth in which a major portion of the root system is concentrated, (b) by causing an extra quantity of energy to be utilized by cells growing in a highly compacted media (Barnes, 1971), thus affecting emergence potential and by reducing plant population due to lower percentage emergence. Therefore, when other plant growth conditions are adequate, increases in soil strength will reduce the rate of seedling emergence which affects critical time and percentage emergence. The seed-moisture absorption rate decreased somewhat with an increase in applied air pressure and increased slightly with an increase in temperature (Henry, 1969). Cone penetrometer index ($N/m^2$) was used as a soil impedance parameter. Seedling emergence is inhibited by a surface crust, and the shoot may be diverted horizontally until it encounters a crack through which it may emerge, thus slowing the rate of emergence (40). Seedling may strike a crust of sufficient strength to preclude emergence (Taylor, 1971 in: Barnes, 1971).
The growth behavior of the seedling is a function of the elapsed time \((t)\). A related basic parameter is the characteristic time factor of growth \((t_g)\). This is a characteristic property of the seed defined by equation 5.11.

5.1.2 Formation of \(\Pi\) - terms

The \(\pi\) - terms were formed by the usual dimensional analysis technique (156) for the seedling emergence force system and the critical time system and are given in Table 5.

5.1.3 Development of prediction equations

a) Seedling force system

The system equation relating the seedling force number \((\Pi_{d1})\) with other independent \(\pi\)-terms is given as:

\[
\Pi_{d1} = \phi_1 \cdot \Pi_2^{n_2} \cdot \Pi_3^{n_3} \cdot \Pi_4^{n_4} \cdot \Pi_5^{n_5} \quad \cdots \quad (5.2)
\]

where \(\Pi_{d1}\) = Dependent \(\pi\)-term, \(\Pi_2, \cdots, \Pi_5\) = Independent \(\pi\)-terms and \(\phi\) and be a function of independent \(\pi\)-terms. Equation (5.2) can be rewritten as:

\[
\Pi_{d1} = \Psi_1 \cdot \Pi_{d12} \cdot \Pi_{d13} \cdot \Pi_{d14} \cdot \Pi_{d15} \quad \cdots \quad (5.3)
\]

\[
\Pi_{d12} = f(\Pi_2) \quad \cdots \quad (5.4)
\]

\[
\Pi_{d13} = f(\Pi_3) \quad \cdots \quad (5.5)
\]

\[
\Pi_{d14} = f(\Pi_4) \quad \cdots \quad (5.6)
\]

\[
\Pi_{d15} = f(\Pi_5) \quad \cdots \quad (5.7)
\]

where \(\Pi_{d11}\) is the value of \(\Pi_{d1}\) when \(\Pi_i\) is varied over a certain range keeping other independent \(\pi\)-terms constant throughout and \(i = 2, 3, 4, 5\). The concept of component experiments (156) was used to obtain equations (5.4) to (5.7). Equations (5.4) and (5.7) were developed by Goyal, et.al.,
Table 5. List of Pi-terms for the critical time system and seedling force system.

<table>
<thead>
<tr>
<th>Dimensionless Pi-term</th>
<th>Physical Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CRITICAL TIME SYSTEM:</strong></td>
<td>$\Pi_d^2 = \frac{t_c}{t_g}$</td>
</tr>
<tr>
<td>$\Pi_2 = Z = (\theta_a - \theta_L)/(\theta_H - \theta_L)$</td>
<td>Ratio of critical time to characteristic time of growth. Dependent variable.</td>
</tr>
<tr>
<td>$\Pi_3 = X$</td>
<td>Environmental temperature index.</td>
</tr>
<tr>
<td>$\Pi_4 = Y$</td>
<td>Seed moisture content at planting, % db.</td>
</tr>
<tr>
<td>$\Pi_5 = \frac{C_1d^3}{J_1E_1m_1}$</td>
<td>Soil moisture content, percent db.</td>
</tr>
<tr>
<td>$\Pi_6 = \frac{C_1d^3}{J_1E_1m_1}$</td>
<td>Index of ratio of soil impedance to the initial internal (stored) energy in the seed. It was designated as soil impedance/seed energy ratio.</td>
</tr>
</tbody>
</table>

| **SEEDLING FORCE SYSTEM:** | $\Pi_d^1 = f(\Pi_2, \Pi_3, \Pi_4, \Pi_5)$ |
| $\Pi_d^1 = f\left(\frac{1}{C_1J_1E_1m_1}\right)$ | This is an index of the ratio: Work done by seedling against soil impedance to stored energy in the seed. It was designated as "Seedling Force Number." |
| $\Pi_2 = Z = (\theta_a - \theta_L)/(\theta_H - \theta_L)$ | Environmental temperature index. |
| $\Pi_3 = X$ | Seed moisture content at planting, % db. |
| $\Pi_4 = Y$ | Soil moisture content, percent db. |
| $\Pi_5 = \frac{t}{t_c}$ | Ratio of elapsed time to critical time (Time at which seedling attains its maximum force). It was designated as time index. |
| $\Pi_7 = \frac{G^3m_1}{J^2E_1C_1}$ | Index of ratio of work done by seedling against the gravity restraint to the product of initial stored energy and the soil impedance. Effect of $\Pi_7$ was neglected. |
1979. Modified forms of these equations are as follows:

\[ \Pi_{d12} = (-294.2 + 2247.9 \Pi_2 - 2002.0 \Pi_2^2) \times 10^{-14} \quad \ldots (5.8) \]

\[ \Pi_{d15} = (-149.5 \Pi_5 + 496.9 \Pi_5^2) \times 10^{-14} \]

\text{for } 0 \leq \Pi_5 \leq 1.0 \quad \ldots (5.9)

\[ \Pi_{d15} = (2748.0 - 3470.2 \Pi_5 + 1106.4 \Pi_5^2) \times 10^{-14} \]

\text{for } 1 \leq \Pi_5 \leq 1.5 \quad \ldots (5.10)

In this study \( \Pi_2, \Pi_5 \) were kept constant throughout and \( \Pi_{d13} \) and \( \Pi_{d14} \) were evaluated.

b) Critical time system

The system equation relating the critical time \( (t_c) \) with other independent \( \Pi \)-terms is given as:

\[ \Pi_{d2} = \frac{t_c}{t_g} = \phi_2 \cdot \Pi_2 \cdot \Pi_3^2 \cdot \Pi_4 \cdot \Pi_6^2 \ldots \ldots \ldots (5.11) \]

where \( \Pi_{d2} \) = Dependent \( \Pi \)-term; \( \Pi_2, \Pi_3, \Pi_4 \) and \( \Pi_6 \) are independent \( \Pi \)-terms. Equation (5.11) is rewritten as:

\[ \Pi_{d2} = \psi_2 \cdot \Pi_{d22} \cdot \Pi_{d23} \cdot \Pi_{d24} \cdot \Pi_{d26} \ldots \ldots \ldots (5.12) \]

or \[ \frac{t_c}{t_g} = \psi_2 \cdot \Pi_{d22} \cdot \Pi_{d23} \cdot \Pi_{d24} \cdot \Pi_{d26} \ldots \ldots \ldots (5.13) \]

where \[ \Pi_{d22} = f(\Pi_2) \ldots \ldots \ldots (5.14) \]

\[ \Pi_{d23} = f(\Pi_3) \ldots \ldots \ldots (5.15) \]

\[ \Pi_{d24} = f(\Pi_4) \ldots \ldots \ldots (5.16) \]

\[ \Pi_{d26} = f(\Pi_6) \ldots \ldots \ldots (5.17) \]

where \( \Pi_{d21} \) is the value of \( \Pi_{d2} \) when \( \Pi_i \) is varied over a certain range keeping other independent \( \Pi \)-terms constant throughout and \( i = 2, 3, 4, 6 \).

The concept of component experiments was used to obtain equations (5.14) to (5.17). Equations (5.14) and (5.17) were developed by Goyal, et al., 1978. Modified forms of these equations are given on next page.
\[
\begin{align*}
\log_e (t_c) &= 4.434 - 0.1202 \log_e (\Pi_2) \quad \cdots \cdots (5.19) \\
\log_e (t_c) &= 3.444 - 0.1073 \log_e (\Pi_6) \quad \cdots \cdots (5.19) \\
or \quad \Pi_{d22} &= \frac{t_{c2}}{84.29} = (\Pi_2)^{-0.1202} \quad \cdots \cdots (5.20) \\
\Pi_{d26} &= \frac{t_{c6}}{32.08} = (\Pi_6)^{-0.1073} \quad \cdots \cdots (5.21)
\end{align*}
\]

In this study $\Pi_2$, $\Pi_6$ were kept constant throughout and $\Pi_{d23}$ and $\Pi_{d24}$ were evaluated.

5.1.4 Experimental schedule

The Williams variety of soybean and Crosby silt loam soil were used for this study. Experiments to measure emergence force were conducted at seed moistures of 8, 12, 14.5, 20, 25% (db) and at soil moisture of 12, 15, 18, 21, 24% (db). Each test run had four replications. The ambient temperature and soil impedance (cone index) were 25°C and 660 kPa respectively and were kept constant throughout the experiment. The experimental schedule with values of pi-terms is given in Table 6.

5.2 Experimental Methods

5.2.1 Seedling force measurements.

The aluminum ring (10 cm outside diameter, 1.25 cm width and 0.312 cm thick) transducer using foil-type electric resistance strain gages in a Wheatstone bridge configuration (figures 5 and 6) was sensitive enough to permit readings of seedling force to the nearest 1 gm. A 24-point thermocouple recorder was modified into an 8-channel, 1-mv recorder which recorded the signal sensed by the transducer after it has been conditioned by the strain-gage conditioner unit. The apparatus used is shown in Figure 7.

Crosby silt loam was sieved through a 0.625 cm sieve before the required amount of water was added to bring it to the desired moisture
Table 6. Experimental schedule for seedling force number and critical time studies.

<table>
<thead>
<tr>
<th>Dependent Variable</th>
<th>( \Pi_2 ) ( (=Z) )</th>
<th>( \Pi_3 ) ( (=X) )</th>
<th>( \Pi_4 ) ( (=Y) )</th>
<th>( \Pi_5 ) ( (=t/\tau_c) )</th>
<th>( \Pi_6 ) ( (=C_1d^3/J_1E_1m_1) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical time index</td>
<td>.525±.025</td>
<td>8.0</td>
<td>18.0±0.5</td>
<td>-</td>
<td>3.717x10^{-5}</td>
</tr>
<tr>
<td>( t_c )</td>
<td>.525±.025</td>
<td>12.0</td>
<td>18.0±0.5</td>
<td>-</td>
<td>3.717x10^{-5}</td>
</tr>
<tr>
<td>( = \frac{t_c}{t_g} )</td>
<td>.525±.025</td>
<td>14.5</td>
<td>18.0±0.5</td>
<td>-</td>
<td>3.717x10^{-5}</td>
</tr>
<tr>
<td>.525±.025</td>
<td>20.0</td>
<td>18.0±0.5</td>
<td>-</td>
<td>3.717x10^{-5}</td>
<td></td>
</tr>
<tr>
<td>.525±.025</td>
<td>25.0</td>
<td>18.0±0.5</td>
<td>-</td>
<td>3.717x10^{-5}</td>
<td></td>
</tr>
<tr>
<td>.525±.025</td>
<td>14.5</td>
<td>12.0±0.5</td>
<td>-</td>
<td>3.717x10^{-5}</td>
<td></td>
</tr>
<tr>
<td>.525±.025</td>
<td>14.5</td>
<td>15.0±0.5</td>
<td>-</td>
<td>3.717x10^{-5}</td>
<td></td>
</tr>
<tr>
<td>.525±.025</td>
<td>14.5</td>
<td>18.0±0.5</td>
<td>-</td>
<td>3.717x10^{-5}</td>
<td></td>
</tr>
<tr>
<td>.525±.025</td>
<td>14.5</td>
<td>21.0±0.5</td>
<td>-</td>
<td>3.717x10^{-5}</td>
<td></td>
</tr>
<tr>
<td>.525±.025</td>
<td>14.5</td>
<td>24.0±0.5</td>
<td>-</td>
<td>3.717x10^{-5}</td>
<td></td>
</tr>
<tr>
<td>Seedling force number</td>
<td>.525±.025</td>
<td>8.0</td>
<td>18.0±0.5</td>
<td>1.0</td>
<td>-</td>
</tr>
<tr>
<td>( f_1^3 )</td>
<td>.525±.025</td>
<td>12.0</td>
<td>18.0±0.5</td>
<td>1.0</td>
<td>-</td>
</tr>
<tr>
<td>( = \frac{f_1}{C_1J_1E_1m_1} )</td>
<td>.525±.025</td>
<td>14.5</td>
<td>18.0±0.5</td>
<td>1.0</td>
<td>-</td>
</tr>
<tr>
<td>.525±.025</td>
<td>20.0</td>
<td>18.0±0.5</td>
<td>1.0</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>.525±.025</td>
<td>25.0</td>
<td>18.0±0.5</td>
<td>1.0</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>.525±.025</td>
<td>14.5</td>
<td>12.0±0.5</td>
<td>1.0</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>.525±.025</td>
<td>14.5</td>
<td>15.0±0.5</td>
<td>1.0</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>.525±.025</td>
<td>14.5</td>
<td>18.0±0.5</td>
<td>1.0</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>.525±.025</td>
<td>14.5</td>
<td>21.0±0.5</td>
<td>1.0</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>.525±.025</td>
<td>14.5</td>
<td>24.0±0.5</td>
<td>1.0</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

\( J_1 = 1.00 \text{ N.m/J}, \ E_1 = 2.471x10^7 \text{ J/kg}, \ m_1 = 0.2 \text{ g/seed}, \)

\( d = 0.642 \text{ cm}, \ C_1 = 660 \text{ kPa (or 6.75 kgf/sq.cm)} \)

* Crosby silt loam soil

**Williams variety of soybean
This circuit duplicated 10 times - common power supply.

**STRAIN GAGE CONDITIONER**

**POWER SUPPLY**

Figure 5. Strain gage signal conditioner and power supply.
Figure 6. Emergence unit with ring transducer.
1. Upper emergence force unit.
2. Lower emergence force unit.
3. Support for transducer.
4. Aluminum ring force transducer.
5. Wire leads.
Figure 7. Instrumentation for soybean seedling force studies. From left: Growth chamber, static strain indicator, power supply, strain gage signal conditioning and balancing unit, and 6-channel recorder.
content. It was then sieved (Figure 8) through 0.625 cm and 0.312 cm sieves successively so as to get samples of average particle size 0.159 cm and 0.476 cm respectively. Soil of average size 0.265 cm was prepared by mixing two parts by weight of soil of average particle size 0.159 cm and one part of soil of average particle size 0.476 cm. Moisture content of the soil sample was determined by oven-drying at 105°C for 24 hours. A mechanical analysis of the soil sample is given in Appendix-A. A moisture equivalent curve for this soil is given in Appendix-B.

The soil so prepared was held in place in the upper container of size 7.6 cm I.D, 5 cm deep with the help of double-layered cheese-cloth. A probe 2.07 cm in diameter and .794 cm deep was used to provide an indentation underneath the upper soil layer (Figure 9) so that the emergence unit could allow the hypocotyl of the germinating seed to grow vertically into the upper soil layer. The cone index of this soil was then determined using ASAE recommendation # R 313.1 (ASAE Yearbook, 1978). This upper container had the soil compacted to the desired cone index of 660 kPa in the series of tests. The soil in the lower container of the emergence unit (shortening can) was subjected to a compaction pressure that produced a cone index of 0.9 kPa and which was thought to be sufficient to provide vertical and lateral support for the seedling without restricting root growth (50). The desired compaction pressure was obtained with the help of a compaction unit shown in Figure 10. The seed was brought to the desired moisture by adding the required amount of water to the sample if it was found deficient in the moisture content. Then it was placed for two to three days in a refrigerator in a sealed plastic bag which was stirred a number of times for uniform distribution of moisture in the sample. If the sample was found in excess of the desired moisture content, it was allowed
Figure 8. Preparation of soil used in the seedling force studies.
Figure 9. Lower face of upper emergence force unit showing an indentation underneath to prevent lateral seedling movement.
Figure 10. Left: Compaction unit showing compaction platform (1), indentation probe (2), pumping lever (3), pressure release lever (4) and pressure gauge (5). Right: Soil in the upper emergence unit is being compacted.
to dry. The moisture content (dry basis) of the seed sample was determined by oven-drying at 103°C for 48 hours (36,166). A single seed of the soybean (Williams) sample so prepared was pressed gently into the soil surface in the lower container of the germinating unit.

The upper container was suspended from the ring transducer (Figure 6). Then this upper unit was carefully lowered until the deflection of the recorder pen showed it had just touched the layer of soil in the lower unit. It was made certain that the seed, pressed in the lower unit, was directly below the indentation provided underneath the upper unit. The force on the ring transducer due to the weight of the upper unit was then balanced out with the balancing unit provided with the strain-gage signal conditioner. The pen on the recorder was brought to the reference point. For moisture conservation small petri dishes filled with water were placed around the units which were placed in the growth chamber. Two wet burlap bags were placed below the force measuring units. The burlap bags were kept wet by spraying water on them at least once every two days. The containers (germinating units) were also covered with plastic bags to conserve moisture.

The desired temperature was maintained automatically throughout the test run in the growth chamber. As the moisture content of the soil medium did not change during the series of tests it was assumed that penetration resistance of the soil remained the same. After 2 or 3 hours, the instrument was balanced again and the unit was left to run undisturbed for 8-10 days (Figure 11).

The signal from the strain-gage bridge was amplified by the conditioning unit and recorded continuously as the seedling developed force trying to emerge through the upper unit. The signal recorded on the chart paper
Figure 11. Seedling force units in the controlled temperature chamber. Plastic covers and petri dishes half filled with water help retain moisture.
(with chart speed of 2.5 cm/8 minutes) was in hundredth of one millivolt. The calibration constant was obtained for each ring transducer so as to convert the recorded data into Newtons (Figure 12).

5.2.2 Hypocotyl diameter measurements

When the test run in 5.2.1 was completed, the seedling was carefully taken from each germinating unit and hypocotyl diameter was measured with a micrometer gauge. The hypocotyl diameter measurements were taken for ambient temperatures of 15', 20', 26', 32'0 and at soil impedances of 112, 225, 450, 660 kPa.

5.2.3 Critical time measurements

When the test run in 5.2.1 was completed, the data points were read from the chart paper. The elapsed time, at which the force was observed to be maximum, was taken as the critical time. The mean seed diameter of the seed sample was determined by averaging the diameters along three mutually perpendicular axes (Figure 13) and was found to be 0.642 cm.

5.2.4 Energy content determinations

In the absence of any data available on the energy content of soybeans calorimetry experiments were conducted to obtain the desired data. The energy content values were determined for Williams variety of soybean.

5.2.4.1 Experimental procedure

The operation of the bomb calorimeter (Figure 14) involved the burning of a sample pellet prepared from the soybean flour with the sample weighing approximately 1.00 gram. The bomb cylinder was filled with oxygen to a pressure of 30 atmospheres. The bomb cylinder retained all of the products of combustion except the heat which was transferred from the bomb cylinder to the surrounding water. The rise in the water temperature was measured.
Figure 12. Block diagram of seedling thrust measurement procedure.
\[ a = \text{seed diameter in x-direction.} \]
\[ b = \text{seed diameter in y-direction.} \]
\[ c = \text{seed diameter in z-direction.} \]
\[ d = \frac{(a + b + c)}{3} = \text{mean seed diameter.} \]

**Figure 13.** Determination of mean seed diameter of soybean (152).
Figure 14. Oxygen bomb calorimeter (225).
The amount of gross energy present in the sample was calculated using the relationship \( E_1 = \frac{(E_1 + E_2)}{m_1} \), where \( E_1 \) = gross energy in calories/grams-mass; \( E_1 = 1368 \) calories/°F (amount of energy required to raise temperature of 2000 gms of water by 1°F); \( \theta_1 \) = temperature rise in the water, °F; \( E_2 \) = Correction factor in calories due to heat of formation of nitric acid (it is measured by titrating entrapped nitrogen in the bomb cylinder with sodium carbonate of normality 0.0726N @ 1 ml of sodium carbonate = 1 calorie); \( E_3 \) = Correction factor in calories due to heat of combustion of fuse wire @ 1 cm of fuse wire = 2.3 calories; \( m_1 \) = mass of pellet sample in grams. \( E_1 \) was then converted into Joules/kg.

The value of internal energy \( (E_1) \) was found to be \( 2.471 \times 10^7 \) J/kg.

5.3 Results and discussion

The regression analysis was applied to find coefficients. A computer statistical package, SAS, was used for this purpose. The raw data are presented in Appendixes C and D. The observed data and predicted values of seedling force number and critical time, based upon statistically determined relationships, are summarized in Appendix E.

5.3.1 Effect of seed moisture \( (\Pi_3) \) on critical time \( (t_c) \)

The following relationship was obtained:

\[
\log(t_c) = 5.497 - 0.3563 \log_e(\Pi_3) \]

\[(5.22)\]

The regression coefficients were significant at the 1% level. The plot of critical time versus \( \Pi_3 \) (Figure 45) showed critical time and \( \Pi_3 \) to be negatively correlated \( (R^2 = 0.93) \) within the range studied. Taylor (1971) suggested soaking the seeds before planting to speed emergence time in high-strength soil. My results support this technique. Hunter and Erickson (1952) mentioned a minimum seed moisture for germination as 50 percent for
\[ \Pi_2 = 0.525 \pm 0.025 \]
\[ \Pi_4 = 18.0 \pm 0.50 \]
\[ \Pi_6 = 3.717 \times 10^{-5} \]

Each data point is a mean of 4 observations.

\[ t_c = 243.96 \, \Pi_3 \]
\[ (R = 0.93) \]

**Figure 15. CRITICAL TIME VS. SEED MOISTURE**
soybeans. At 50% seed moisture, critical time using equation 5.22 will be 61 hours. On the other hand at 5% seed moisture, the critical time is 138 hours. Although seed may not germinate at extremely low moisture levels, the equation 5.22 yields a critical time of 244 hours for a 1% moisture level.

5.3.2 Effect of soil moisture ($\Pi_4$) on critical time ($t_c$)

The following relationship was obtained:

$$\log_e(t_c) = 7.169 - 0.9251 \log_e(\Pi_4) \quad \ldots \ldots (5.23)$$

The regression coefficients were significant at the 1% level. The plot of critical time versus $\Pi_4$ (Figure 16) showed critical time and $\Pi_4$ to be negatively correlated ($R^2 = 0.99$) within the range studied. Similar results have been reported by Jensen, et al., (1972) for alfalfa and tall wheatgrass. Hanks and Thorp (1956 and 1957) reported that the ultimate seedling emergence of wheat, grain sorghum and soybeans was approximately the same when the soil moisture is maintained between field capacity and permanent wilting percentage, if other factors were optimum. The rate of emergence, however, was related directly to the soil moisture content.

The results of this study indicate that soil moistures near field capacity are more favorable as maximum seedling force is exerted earlier. In dry soils, seedlings may never develop required seedling emergence force.

5.3.3 Effect of seed moisture ($\Pi_3$) on seedling force number ($\Pi_{d13}$)

The following relationship was obtained:

$$\Pi_{d13} = (386.3 - 0.12 \Pi_3^2) \times 10^{-14} \quad \ldots \ldots (5.24)$$

The regression coefficients were significant at the 1% level. The coefficient of determination was 0.98. The plot of $\Pi_{d13}$ versus $\Pi_3$ (Figure 17) showed decreases in seedling force number as $\Pi_3$ was increased from 8 to 25 percent. Henry (1969) mentioned the potential danger of
$\Pi_2 = 0.525 \pm 0.025$

$\Pi_3 = 14.5$

$\Pi_5 = 3.717 \times 10^{-5}$

Each data point is a mean of 4 observations.

$\tau_c = 1298.54 \frac{1}{\Pi_4^{0.9251}}$

$(R^2 = 0.99)$

Figure 16. CRITICAL TIME VS. SOIL MOISTURE
\( \Pi_2 = 0.525 \pm 0.025 \)
\( \Pi_4 = 18.0 \pm 0.50 \)
\( \Pi_5 = 1.00 \)
\( C_1 = 660 \text{ kPa (or 6.75 kgf/cm}^2\text{)} \)

Each data point is a mean of 4 observations.

\[ \Pi_{d1} = \{386.28 - 0.12(\Pi_3)^2\} \]
\[ R^2 = 0.98 \]

**Figure 17.** SEEDLING FORCE NUMBER VS. SEED MOISTURE.
exhausting seed reserves (seed energy) before emergence when seed is highly stressed. Higher initial seed moisture is favorable until a moisture content necessary for germination is approached and subsequently seed has to do less work.

5.3.4. Effect of soil moisture ($\Pi_4$) on seedling force number ($\Pi_{d14}$)

A second degree polynomial relating $\Pi_4$ with $\Pi_{d14}$ was fitted to the data. The following relationship was obtained:

$$\Pi_{d14} = (55.8 \Pi_4 - 1.99 \Pi_4^2) \times 10^{-14} \quad \ldots \ldots (5.25)$$

The regression coefficients were significant at the 1% level. The coefficient of determination was 0.99. The plot of $\Pi_{d14}$ versus $\Pi_4$ (Figure 18) showed that increases in $\Pi_4$ from 12 to 15 caused increases in seedling force number and further increases in $\Pi_4$, to 24, caused reductions in seedling force number. Hanks and Thorp (1956 and 1957) reported that the rate of emergence was related to the soil moisture content. Since the rate of emergence is related to seedling emergence force, the soil moistures near field capacity favor early emergence. Seeds appear to develop less force at soil moistures near field capacity as compared to soil moistures near permanent wilting percentage.

5.3.5 Generalized prediction equations

5.3.5.1 Critical time

Equations 5.20, 5.21, 5.22 and 5.23 were combined (Murphy, 1950) to get the generalized prediction equation for 'critical emergence force time' as follows:

$$\Pi_{d2} = \frac{t_c}{t_g} = \Pi_2 \cdot \Pi_3 \cdot \Pi_4 \cdot \Pi_6 \quad \ldots \ldots (5.11)$$

The slope of fitted lines (equations 5.20, 5.22, 5.23, 5.21) gave values of exponents $n_2$, $n_3$, $n_4$, $n_6$ as $-0.1202$, $-0.3563$, $-0.9251$, and $-0.1073$ respectively. The value of characteristic time factor of growth
\[ \Pi_2 = 0.525 \pm 0.025 \]
\[ \Pi_3 = 14.5 \]
\[ \Pi_5 = 1.00 \]
\[ C_1 = 660 \text{ kPa (or 6.75 kgf/cm}^2 \]

Each data point is a mean of 4 observations.

\[ \Pi_{d1} = (55.83(\Pi_4) - 1.99(\Pi_4)^2) \]
\[ R = 0.99 \]

**Figure 18. Seedling Force Number vs. Soil Moisture.**
was calculated to be 1072 hours. The prediction equation 5.11
then becomes:

\[
\frac{t_c}{1072} = \left[ \frac{\theta_a - \theta_L}{\theta_H - \theta_L} \right]^{-0.1202} \cdot \left[ X_1 \right]^{-0.3563} \cdot \left[ Y_1 \right]^{-0.9251} \cdot \left[ \frac{C_1}{d^3} \right]^{-0.1073}
\]

The correlation coefficient for the line \( t_{c,\text{cal}} = t_{c,\text{obs}} \) was found to be 0.97. The limitations of the prediction equation 5.26 are:
(a) Williams variety of soybean, (b) Crosby silt loam soil, (c) Temperature range of 15 to 32\(^\circ\)C, (d) Seed moisture range of 8-25\% (db), and (e) Soil moisture range of 12-24\% (db).

5.3.5.2 Seedling force number

Eqs. 5.8 to 5.10, 5.24 and 5.25 were substituted in equation 5.3
(Murphy, 1950) to get the generalized prediction equation as follows:

\[
\Pi d_1 = (0.24370 \times 10^{-21}) \cdot (-294.2 + 2247.9 \Pi_2 - 2002.0 \Pi_2^2)
\]

\[
(386.3 - 0.12 \Pi_2) \cdot (55.8 \Pi_4 - 1.99 \Pi_4^2) \cdot (-149.5 \Pi_5 + 496.9 \Pi_5^2)
\]

for \( 0 \leq \Pi_5 \leq 1.0 \)

\[
\Pi d_1 = (0.22319 \times 10^{-21}) \cdot (-294.2 + 2247.9 \Pi_2 - 2002.0 \Pi_2^2)
\]

\[
(386.3 - 0.12 \Pi_2) \cdot (55.8 \Pi_4 - 1.99 \Pi_4^2) \cdot (2748.0 - 3470.2 \Pi_5 + 1106.4 \Pi_5^2)
\]

for \( 1 \leq \Pi_5 \leq 1.5 \)

The correlation coefficient for the line \( \Pi d_1,\text{cal} = \Pi d_1,\text{obs} \) was found to be 0.99. The limitations of the prediction equations 5.27 and 5.28 are: (a) Williams soybean variety, (b) Crosby silt loam soil, (c) temperature range of 15-32\(^\circ\)C, (d) seed moisture range of 8-25\% (db), (e) soil moisture range of 12-24\% (db).

5.3.5.3 Application of generalized prediction equations

Equation 5.26, relating critical time with physical parameters that affect the critical time system (Table 5), can be used for predicting the time at which seedling would attain its maximum force at given environmental conditions.
Equations 5.27 and 5.28, relating seedling force number with physical parameters (Table 4) that affect the seedling force system, can be used for predicting soybean seedling force at given environmental conditions. Using these predictions, management techniques can be identified that would favor early emergence of seedlings through crusted soils.

5.3.6 Effect of temperature and soil impedance on hypocotyl diameter of soybean

The raw data are presented in Appendix F. Table 7 gives the relationship between the hypocotyl diameter and ambient temperature at varying soil impedance.

Second degree polynomials (Figure 9) were fitted to the data (Appendix F). Regression analysis revealed that all regression coefficients were significant (Table 7). Increased compaction above the developing seedling caused increased hypocotyl diameter within the temperature range studied. It is hypothesized that increase in hypocotyl diameter was due to resistance offered to the upward conduction of water/inorganic salts through the xylem, to the downward conduction of principal food stored in the cotyledons and to the elongation of the hypocotyl (23, 218, 219, 220).

Increases in temperatures from 15° to 26°C caused increases in hypocotyl diameters. Further increases in temperatures, to 32°C, caused reductions in hypocotyl diameters due probably to increased respiration rate in the cells at higher temperatures. A similar relationships have been reported for hypocotyl elongation of cotton, soybeans (83, 94, 104) as was noted in the literature review.
Table 7. Relationship between hypocotyl diameter and ambient temperature.

\[ d_h = a_1 + a_2 \theta_a + a_3 \theta_a^2 \]

<table>
<thead>
<tr>
<th>Soil resistance (kgf/cm²)</th>
<th>Regression coefficients</th>
<th>Coefficient of determination (R²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(a_1)</td>
<td>(a_2)</td>
</tr>
<tr>
<td>1.12</td>
<td>-0.5647*</td>
<td>+0.0699*</td>
</tr>
<tr>
<td>2.25</td>
<td>-0.6138</td>
<td>+0.0769**</td>
</tr>
<tr>
<td>4.50</td>
<td>-0.6068*</td>
<td>+0.0804*</td>
</tr>
<tr>
<td>6.75</td>
<td>-0.8650*</td>
<td>+0.1037*</td>
</tr>
</tbody>
</table>

* Significant at the 5% level of significance.

** Significant at the 1% level of significance.
Figure 19. Hypocotyl diameter vs temperature.
CHAPTER 6
MECHANICAL PROPERTIES OF SOIL CRUST

Additional information is necessary pertaining to mechanical properties of soil crust so that the force equations in chapter 5 can be used to predict stresses in soil crusts by emerging dicot seedlings. Tests were therefore conducted to determine soil crust properties such as thickness, Poisson's ratio, modulus of elasticity, bulk density, modulus of rupture, and sub-soil reaction modulus.

6.1 Modulus of rupture

A crosby silt loam soil of average size 0.265 cm was prepared by mixing two parts by weight of soil of average aggregate size 0.159 cm and one part of soil of average aggregate size 0.476 cm. A mechanical analysis of the soil sample indicated that the soil contained 18.7 percent sand, 58.4 percent silt and 22.9 percent clay (Appendix A).

The soil sample was placed in the sheet metal tray (10 x 30 x 37.5 cm) with bottom drilled with 0.625 cm dia holes to allow moisture transfer into and out of the soil sample. After applying a surface compaction of 6.9 kPa, the trays were placed under the rainfall simulator (Figure 20) to receive rainfall intensity of 3.75 cm/hour for a total rainfall of 2.5 cm. After all surface water had infiltrated into the soil, the soil samples were placed on burlap bags under the heat lamps (Figure 21) to receive radiant heat of 390 cal/cm²-day for 5 days. The burlap bags were kept wet at all times.
Figure 20. The rainfall simulator used to provide rainfall intensity of 3.75 cm/hour for a total rainfall of 2.5 cm.
Figure 21. The soil samples receiving the heat treatment @ 390 cal/cm² - day for 5 days.
Upon completion of the fifth day of drying under the heat lamps, soil crust samples were carefully taken with a 5 x 8.75 cm template and a thin-bladed knife (Figure 22). The crust sample was then placed with its top side down on the two knife edge supports 6 cm apart for determination of Modulus of rupture (Figure 23). The loading probe of the Instron Testing Machine was operated at 0.5 cm per minute and the chart speed was 20 cm/minute. The load cell sensitivity was 5 kg for a full scale deflection of the recording needle.

Mean modulus of rupture value was found to be 12.1 kgf/cm² for the above sample (Appendix G).

6.2. Bulk density of soil crust

For bulk density measurements, the Saran resin F310 solution (specific gravity 1.3) was used to provide an impermeable plastic coating on the soil crust sample.

To prepare the plastic solution, a weighed container was filled with a commercial grade acetone to about 3/4 of its volume. From the weight of the solvent, the weight of Dow Saran Resin F310 required to obtain a resin - solvent ratio of 1:7 was calculated and was added to the solvent. The plastic solution was prepared under an exhaust hood to avoid inhaling of fumes. The mixture was left overnight to allow complete mixing of Saran in solvent. The mixture was then stored in one gallon metal can and the container was kept tightly closed to prevent evaporation of the solvent.

The soil crust sample prepared in section 6.1 was held by fingers and was briefly immersed in the plastic solution. The immersed sample was then placed on the fine wires under the exhaust hood and the coating
Figure 22. The soil crust sample was taken with template and a thin-bladed knife for determination of bulk density and modulus of rupture.
Figure 23. Determination of modulus of rupture of soil crust sample. The loading rate was 0.5 cm/hour and the chart speed was 20 cm/hour.
was allowed to dry for 30 minutes (Figure 24).

The coated soil crust sample was weighed in the air (Figure 25) and in the water (Figure 26). The volume of water displaced was the volume of the coated crust sample (Archimedes' Principle). The correction was applied for the weight and volume of plastic coat on the soil crust sample.

The bulk density of the soil crust at a moisture content of 6.1 percent (dry basis) was found to be 1.64 g/cm³ (Appendix H).

6.3 Soil crust thickness

There is no standard technique, available in the literature, to find the soil crust thickness. For objective evaluation and standardization of soil crust thickness, it was assumed that the bulk density varied linearly from the soil crust surface to the sub-soil where it became constant. Average thickness of the crust sample was calculated from volume and area of the soil crust sample. The bulk density of sample of desired thickness was determined by Saran immersion technique. The bulk density versus thickness data are presented in Appendix I.

Non-linear regression analysis was used to determine the values of A and B in the equation \( \rho_B = A + (B-A) \exp (-x) \) where \( \rho_B \) = bulk density of the soil crust sample at sample thickness \( x \). The following relationship was obtained:

\[
\rho_B = 1.495 + (1.781 - 1.495) \exp (-x)
\]

or

\[
\rho_B = 1.495 + 0.286 \exp (-x) \quad \cdots \cdots \cdots \text{(6.1)}
\]

Equations for tangent were found to be:

\[
\rho'_B = 1.50 \quad \text{at} \ x = 4.17 \quad \cdots \cdots \cdots \text{(6.2)}
\]

\[
\rho'_B = -0.286 x + 1.78 \quad \text{at} \ x = 0 \quad \cdots \cdots \cdots \text{(6.3)}
\]

The thickness of the soil crust sample was determined to be 0.979 cm from equations 6.2 and 6.3 and bulk density versus soil sample thickness plot (Figure 27).
Figure 24. The use of Saran F310 solution for providing impermeable plastic coating on the soil crust sample. From left: Funnel to pour the solution into and out of metal container, immersion can, wire arrangement to dry the coated samples, and the hood to avoid inhaling of fumes.
Figure 25. The coated soil crust sample is being weighed in the air for determination of bulk density. The weighing balance is resting on wooden box.
Figure 26. The coated soil crust sample is being weighed in the water to find the volume of sample by Archimedes' Principle. This volume was used for determination of bulk density of the sample.
Figure 27. Bulk density ($\rho_b$) of crust sample versus sample thickness ($x$) plot.
6.4 The Poisson's ratio and modulus of elasticity of soil crust

A simulated soil crust sample (Figure 28) 6x3.25x1.53 cm was prepared from the crosby silt loam soil to get a smooth surface. The strain gages (MM EA-06-250BG-120, gage factor 2.06, resistance 120 Ω) were bonded on the soil crust surface (Figure 29) in the axial and transverse direction using M-bond 200. Each strain gage was centered at a distance L/4 from the nearest support where L is the distance between supports. The strains at point 'a' and 't' (Figure 30) were recorded with the help of strain gage conditioner and balancing unit (Figure 31).

The stress at point 'a' was calculated using the relationship

\[ \sigma_1 = \frac{3P_1L}{4Eh^2} = 0.5915P_1 \]

The slope of \( \sigma_1 \) versus \( e_a \) plot gave modulus of elasticity of the soil crust. The Poisson's ratio was calculated using the relationship \( \nu = e_a/e_t \). The data are presented in Appendix J. The Poisson's ratio of soil crust was found to be 0.236. The relationship between \( \sigma_1 \) and \( e_a \) was found to be

\[ \sigma_1 = 0.011075 e_a \]

(6.4)

The coefficient of determination was 0.97 and the regression coefficient was significant at the 1 percent level of significance. Equation 6.4 gave the value of modulus of elasticity of soil crust as \( 0.011 \times 10^6 \) kgf/cm².

6.5 Sub-soil reaction modulus

Sub-soil reaction modulus for the Crosby silt loam soil at 14.5% (db) moisture was evaluated by plotting stress (\( \sigma_2 \)) on the soil surface due to the applied force \( P_2 \) versus the sinkage of the 5x5 cm plate (Figure 32). Boussinesq's equation for stresses at the given depth in the sub-soil due to circular loaded area gave the value of limiting depth (\( d_2 \)) as \( \sqrt{\pi/12} \). The container depth was therefore kept 15 cm to avoid effect
Figure 28. The wooden frame (Right) was used to obtain simulated soil crust sample of size $6 \times 3.25 \times 1.53$ cm, and with smooth surface so that strain gages can be bonded on it.
Figure 29. The strain gages were bonded on the simulated soil crust sample in the axial and transverse direction using M-bond 200.
Figure 30. Top: Simple bending test to find Poisson's ratio and modulus of elasticity of crust sample.
Bottom: Location of strain gages, in the axial and transverse direction, on the simulated soil crust sample. The load $P_1$ was applied by pouring water in the plastic bottle and $L$ is the distance between supports, $H$ is the sample thickness, $B$ is the sample width.
Figure 31. Instrumentation to record the strain in the axial and transverse direction developed in the simulated crust sample. The load on the sample was applied by pouring known amount of water in the plastic bottle. The figure shows:

1. Supports
2. Soil sample
3. Sample molding
4. Frame kit
5. Dummy gages
6. Strain indicator
7. Switching and balancing unit.
Figure 32. Determination of sub-soil reaction modulus of crosby silt loam soil. In above figure $e$ is the sinkage of 5x5 cm plate due to applied load $P_2$. 
of container size on the stresses due to 5x5 cm plate. The relationship between the stress ($\sigma_2$) and sinkage of plate ($e$) was found to be

$$\sigma_2 = 0.0973 \ e$$

(6.5)

The coefficient of determination was 0.90 and the regression coefficient was significant at the one percent level of significance. From equation 6.5 the value of sub-soil reaction modulus was found to be 0.0973 kgf/cm$^2$. 
CHAPTER 7

PREDICTION OF SOIL CRUST STRESSES

7.1 Surface bending stresses in soil crust

The values of physical parameters (Table 2), which were obtained experimentally in Chapter 5 and Chapter 6, are as follows:

1. Soil crust thickness : 0.979 cm
2. Poisson's ratio of soil crust : 0.236
3. Modulus of elasticity of soil crust : 0.01107 Mkgf/cm²
4. Bulk density of soil crust : 1.64 g/cm³
5. Sub-soil reaction modulus : 0.0973 Kgf/cm²
6. Soybean seedling emergence force : Equations 5.26 to 5.28
7. Seed spacing down the row (Table 8) : 2.5, 3.75, 5.0, 10.0 cm
8. Hypocotyl radius of soybean seedling at 26°C, 660 kPa, 14.5% (db) seed moisture and 19% db soil moisture (Figure 19) : 0.298 cm

Using a range of values of physical parameters (Table 9) which included above values and equation 4.15, the bending stress number in the Y-direction \( \Pi_{d4} = \sigma_{yy} h^2/\rho \) was predicted on the surface of the soil crust directly above the seedling. The results are presented in Figures 33 to 37. Knowing the maximum seedling force \( P \) and soil crust thickness one can evaluate the maximum surface bending stress generated in the soil crust. The bending stress number depends on environmental conditions and seed/soil characteristic factors because of their correlation with seedling force \( P \), soil crust thickness \( h \), and bending stress \( \sigma_{yy} \).
Table 8. Soybean planting recommendations in Ohio (227).

<table>
<thead>
<tr>
<th>Row width cm</th>
<th>Seeds planted per meter of row</th>
<th>Estimated seed rate kg/hectare</th>
<th>Recommended plants at harvest per meter</th>
<th>Recommended plants at harvest per hectare</th>
</tr>
</thead>
<tbody>
<tr>
<td>17.5 - 20</td>
<td>10 - 13</td>
<td>50 - 124</td>
<td>7-10</td>
<td>358150</td>
</tr>
<tr>
<td>(drilled solid)</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>50.0 - 52.5</td>
<td>33 - 40</td>
<td>62 - 136</td>
<td>20-27</td>
<td>368030</td>
</tr>
<tr>
<td>70.0 - 75.0</td>
<td>33 - 40</td>
<td>44 - 96</td>
<td>20-27</td>
<td>259350</td>
</tr>
<tr>
<td>95.0 - 100.0</td>
<td>33 - 40</td>
<td>32 - 72</td>
<td>20-27</td>
<td>192660</td>
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</table>
Table 9. Values of pi-terms for predicting the bending stress number in the Y-direction.

<table>
<thead>
<tr>
<th>$\Pi_{d4}$</th>
<th>$\Pi_8$</th>
<th>$\Pi_9$</th>
<th>$\Pi_{10}$</th>
<th>$\Pi_{11}$</th>
<th>$\Pi_{12}$</th>
<th>$\Pi_{13}$</th>
<th>$\Pi_{14}$</th>
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</thead>
<tbody>
<tr>
<td>$\sigma_{yy}h^2/P$</td>
<td>b/c</td>
<td>b/a</td>
<td>b/h</td>
<td>x/a</td>
<td>y/b</td>
<td>v</td>
<td>$k_1b/E_c$</td>
</tr>
<tr>
<td>8.4</td>
<td>0.03</td>
<td>2.55</td>
<td>0.0</td>
<td>0.0</td>
<td>0.236</td>
<td>21.962E-6</td>
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<td>12.6</td>
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</tr>
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<td>0.03</td>
<td>2.55</td>
<td>0.0</td>
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</table>
7.2 Interpretation of results

7.2.1 The bending stress number versus seed spacing - hypocotyl radius ratio

Figure 33 shows the effect of the ratio of seed spacing down the row to hypocotyl radius ($\Pi_8$) on the bending stress number in the $Y$-direction ($\Pi_{d4}$) for $\Pi_9 = 0.03$, $\Pi_{10} = 2.55$, $\Pi_{11} = 0.00$, $\Pi_{12} = 0.00$, $\Pi_{13} = 0.236$ and $\Pi_{14} = 0.21962E-4$. The relationship indicates increased $\Pi_{d4}$ with increases in $\Pi_8$. For constant seed spacing down the row, the decreases in hypocotyl radius caused increases in the bending stress parameter because of reduction in area over which the seedling force is distributed. Thus seedlings with small hypocotyl radius, such as monocots, generate relatively large stresses. As seed spacing becomes zero, the stresses in $Y$-direction approach zero which indicate seedling is tending to lift the entire crusted surface and the bending stress parameter in $X$-direction increases.

7.2.2 Bending stress number versus seed spacing - crust thickness ratio

Figure 34 shows the effect of the ratio of seed spacing down the row to soil crust thickness ($\Pi_{10}$) on the bending stress number in the $Y$-direction ($\Pi_{d4}$) for $\Pi_8 = 8.40$, $\Pi_9 = 0.03$, $\Pi_{11} = 0.0$, $\Pi_{12} = 0.0$, $\Pi_{13} = 0.236$, and $\Pi_{14} = 0.21962E-4$. Increases in $\Pi_{10}$ caused reductions in $\Pi_{d4}$. Results indicate that the bending stress parameter increases as seed spacing down the row decreases for constant soil crust thickness.

7.2.3 The bending stress number magnitude between seedling down the row

Figure 35 reveals the effect of dimensionless position coordinate in the $Y$-direction ($\Pi_{12}$) on the bending stress number in the $Y$-direction ($\Pi_{d4}$) for $\Pi_8 = 8.40$, $\Pi_9 = 0.03$, $\Pi_{10} = 2.55$, $\Pi_{11} = 0.0$, $\Pi_{13} = 0.236$, $\Pi_{14} = 0.21962E-4$. The results indicate that the bending stress number
\( \Pi_9 = 0.03 \)
\( \Pi_{10} = 2.55 \)
\( \Pi_{11} = 0.00 \)
\( \Pi_{12} = 0.00 \)
\( \Pi_{13} = 0.24 \)
\( \Pi_{14} = 0.21962 \times 10^{-4} \)

\[ \Pi_{d4} = (\sigma_{yy} k^2 / p) \]

\[ \Pi_8 = b / c \]

Figure 33. Effect of ratio of seed spacing down the row to hypocotyl radius (\( \Pi_8 \)) on bending stress number in \( \gamma \)-direction (\( \Pi_{d4} \)).
\( \Pi_8 = 8.40 \)
\( \Pi_9 = 0.03 \)
\( \Pi_{11} = 0.00 \)
\( \Pi_{12} = 0.00 \)
\( \Pi_{13} = 0.24 \)
\( \Pi_{14} = 0.21962 \times 10^{-4} \)

\[ \Pi_{d4} = \left( \sigma_{yy} h^2 / P \right) \]

\[ \Pi_{10} = b/h \]

Figure 34. Effect of ratio of seed spacing down the row to soil crust thickness (\( = \Pi_{10} \)) on bending stress number in \( y \)-direction (\( = \Pi_{d4} \)).
\[ \Pi_{8} = 8.40 \\
\Pi_{9} = 0.03 \\
\Pi_{10} = 2.55 \\
\Pi_{11} = 0.00 \\
\Pi_{13} = 0.24 \\
\Pi_{14} = 0.21962 \times 10^{4} \]

Figure 35. Effect of dimensionless position coordinate
\( (= \Pi_{12}) \) on bending stress number in Y-direction
\( (= \Pi_{d4}) \)
is maximum directly above the seedling ($\Pi_{12} = 0, 1.0$) and it is a minimum at the mid-point between seedlings down the row.

7.2.4 **Effect of Poisson's ratio upon bending stress number**

Figure 36 indicates a quasi-linear relationship between the bending stress number in the Y-direction ($\Pi_{d4}$) and Poisson's ratio of soil crust for $\Pi_8 = 8.40, \Pi_9 = 0.03, \Pi_{10} = 2.55, \Pi_{11} = 0.0, \Pi_{12} = 0.0, \Pi_{14} = 0.21962B-4$. The bending stress number increased with increases Poisson's ratio of soil crust.

7.2.5 **Bending stress number versus sub-soil and soil crust modulii**

Figure 37 reveals that the bending stress number in the Y-direction ($\Pi_{d4}$) and the index of ratio of sub-soil reaction modulus to soil crust modulus ($\Pi_{14}$) are negatively correlated for $\Pi_8 = 8.40, \Pi_9 = 0.03, \Pi_{10} = 2.55, \Pi_{11} = 0.0, \Pi_{12} = 0.0$, and $\Pi_{13} = 0.236$. For a selected soil crust sample, i.e., with constant sub-soil and soil crust modulii, decreased seed spacing down the row caused increases in bending stress number.

7.3 **Application of results**

Equation 5.26, relating critical time (Time at which seedling attains its maximum force) with physical parameters that effect the critical time system (Table 4), can be used for predicting the time at which a seedling would attain its maximum force under given environmental conditions. Equations 5.27 and 5.28, relating seedling force number with physical parameters (Table 3) that affect the seedling force system, can be used for predicting soybean seedling emergence force at given elapsed time and under given environmental conditions. Using these predictions and the results presented previously in Chapter 6 and Chapter 7, management techniques can be identified that would favor early emergence of
\( \Pi_8 = 8.40 \)
\( \Pi_9 = 0.03 \)
\( \Pi_{10} = 2.55 \)
\( \Pi_{11} = 0.00 \)
\( \Pi_{12} = 0.00 \)
\( \Pi_{14} = 0.21962 \times 10^{-4} \)

**Figure 36.** Effect of Poisson's ratio of soil crust (= \( \Pi_{13} \)) on bending stress number in \( Y \)-direction (= \( \Pi_{d4} \)).
\[ \Pi_{14} = \left( \frac{\phi_r b}{E_c} \right), \times 10^4 \]

Figure 37. Effect of index of the ratio of sub-soil reaction modulus to modulus of elasticity of soil crust \((= \Pi_{14})\) on bending stress number in \(Y\)-direction \((= \Pi_{d4})\).
seedlings through crusted soils.

It is assumed that the emergence will not occur if maximum surface bending stress generated in soil crust directly above the seedling is less than the soil crust strength. The emergence would be expected if the maximum surface bending stress is greater than the soil crust strength. Within the range of variables studied and for modulus of rupture of 12 kgf/cm², all the seedlings mentioned in Table 10 would emerge. Further studies need to be conducted to evaluate the effects of physical parameters on mechanical properties of soil crust.

The results presented previously indicate that closer seed spacing down the row creates increased bending stresses in the Y-direction, until b becomes zero, therefore helping to increase the seedling emergence in crusted soil. These results support soybean planting recommendations (227) which suggest that seed rate be increased to have more plants per meter of row for better emergence in soils which crust badly.

The results presented in section 5.3 support the technique of soaking the seeds before planting to speed emergence time in high-strength soil. This needs further investigation relative to the soaked seeds remaining free of mechanical damage from the mechanical planters. This technique seems to have more application in the under-developed/developing countries where hand or animal power is used for field operations because of small-sized farms. Perhaps the more modern pneumatic type planters would help to alleviate problems associated with mechanical damage to soaked seeds.

7.3.1 Management techniques in crusted soils

Based upon the results presented in Chapters 5, 6 and 7, the following management techniques, which were modified from those suggested by
Table 10. Maximum bending stress values generated in soil crust by emerging soybean seedling.

<table>
<thead>
<tr>
<th>Ambient temperature</th>
<th>Soil moisture</th>
<th>Seed moisture</th>
<th>Mean maximum soybean seedling emergence force</th>
<th>Maximum bending stress in soil crust</th>
</tr>
</thead>
<tbody>
<tr>
<td>°C</td>
<td>% db</td>
<td>% db</td>
<td>gf</td>
<td>kgf/cm²</td>
</tr>
<tr>
<td>26</td>
<td>18</td>
<td>8</td>
<td>400</td>
<td>15.8</td>
</tr>
<tr>
<td>26</td>
<td>18</td>
<td>12</td>
<td>397</td>
<td>15.7</td>
</tr>
<tr>
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<td>18</td>
<td>14.5</td>
<td>396</td>
<td>15.6</td>
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<tr>
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<tr>
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<td>18</td>
<td>14.5</td>
<td>382</td>
<td>15.1</td>
</tr>
</tbody>
</table>

* Using equation 5.26 to 5.28 in Chapter 5.

@ Using values of physical parameters mentioned in section 7.1 and equation 4.15 for the bending stress number generated in soil crust by emerging dicot seedling.
Taylor, 1971, may be used to reduce plant injury from crusting.

1. Soak seeds before planting to speed emergence time.

   This technique is especially useful for under-developed/developing countries where hand labor is used to till the farms. The retention time for the seeds in water needs further investigation so that seeds would not be damaged in the mechanical planters. Use of pneumatic type planters may be more appropriate.

2. Increase the seed rate per meter down the row for increased seedling emergence in crusted soils.

3. Plant seeds in groups (hill-drop) because this would generate greater emergence force to break through the crusted soil.

4. Cover the field (seed-row) with straw or plastic to prevent the soil surface from developing high strength through compaction by rainfall impact. This technique seems to be applicable only to small-sized farms that utilize man or animal power.

5. Plant seeds on the sloping side of furrow if possible as the soil crust is not severe on this portion of the furrow. Also the soil crust strength is less for the sloping side of the furrow (39).

6. Allow plants to exert their maximum force by providing favorable conditions (37,39).

7. Reduce the mechanical impedance of soil surface by adding organic matter (39), soil conditioners (HFAN, VAMA, Phosphoric acid) and fracturing agent (4-tert-butylpyro-catechol).

8. Keep the soil surface moist if possible. Soil moistures near field capacity are more favorable to speed emergence time in crusty soils.

9. Select varieties capable of exerting and rapidly achieving large emergence forces (159,160,161).
10. Break the surface soil crust by tillage to reduce the soil impedance. This may cause some seedling injury.

7.4 Summary of results of this study

Within the ranges of the variables studied, the following results were obtained for Williams soybean variety and crosby silt loam soil.

1. The internal energy for the soybean seed (Williams variety) was found to be $2.47 \times 10^7$ J/kg.

2. The characteristic time factor of growth was found to be approximately 1100 hours.

3. The critical time was negatively correlated with moisture indices and the relationships were exponential.

4. Quadratic relationships between the seedling force number and the moisture indices gave better fits to the experimental data, compared to linear and exponential relationships.

5. The mean maximum values of soybean emergence force were observed to be 3.92, 3.89, 3.88, 3.80, 3.67 N at seed moisture of 8, 12, 14.5, 20, 25 percent (db) respectively and at an ambient temperature of 26°C, soil moisture of 18 percent (db) and cone index of 660 kPa.

6. The mean maximum values of soybean emergence force were observed to be 3.99, 3.96, 3.88, 3.63, 3.16 N at soil moisture of 12, 15, 18, 21, 24 percent (db) respectively and at an ambient temperature of 26°C, seed moisture of 14.5 percent (db) and cone index of 660 kPa.

7. Hypocotyl diameter increased with increased soil impedance above the developing seedling at constant temperature.

8. Hypocotyl diameter was maximum at an ambient temperature of 26°C at constant soil impedance.
9. The bending stress number in the Y-direction directly above the seedling was 37.32 at $b/c = 8.4$, $b/a = 0.05$, $b/h = 2.55$, $x/a = 0.00$, $y/b = 0.00$, $V = 0.236$ and $(k_1b/E_o) = 0.21962E-4$.

10. The bending stress number and the ratio of seed spacing down the row to hypocotyl radius were positively correlated.

11. The relationship between the bending stress number and Poisson's ratio was quasi-linear.

12. The bending stress number and the ratio of seed spacing down the row to soil crust thickness were negatively correlated.

13. The bending stress number and the index of ratio of sub-soil reaction modulus to crust modulus were negatively correlated.
CHAPTER 8

CONCLUSIONS

Within the ranges of variables studied and for Williams soybean variety and crosby silt loam soil, the following conclusions were drawn:

1. The generalized prediction equation for the critical emergence force time for soybean was found to be:

\[
\frac{t_c}{1072} = \left( \frac{\theta_a - \theta_L}{\theta_H - \theta_L} \right)^{-0.1202} \cdot \left[ \begin{array}{c} X_1 \\ Y_1 \end{array} \right] \cdot \left[ \begin{array}{c} \frac{c_1}{d^3} \end{array} \right] = -0.3563 \cdot -0.9251 \cdot -0.1073
\]

\[\cdots \cdots \cdots \cdots \cdots (5.26)\]

2. The generalized prediction equations for the soybean seedling emergence force number were found to be:

\[\Pi d_1 = (0.24370 \times 10^{-21}) \cdot \left( -294.2 + 2247.9 \frac{\Pi}{2} - 2002.0 \frac{\Pi^2}{2} \right) \cdot (386.3 - 0.12 \frac{\Pi^2}{2}) \cdot (55.8 \frac{\Pi}{4} - 1.99 \frac{\Pi^2}{4}) \cdot \left( -149.5 \frac{\Pi}{5} + 496.9 \frac{\Pi^2}{5} \right)
\]

for \( 0 \leq \Pi \leq 1.6 \)

\[\cdots \cdots \cdots \cdots \cdots (5.27)\]

\[\Pi d_1 = (0.22319 \times 10^{-21}) \cdot \left( -294.2 + 2247.9 \frac{\Pi}{2} - 2002.0 \frac{\Pi^2}{2} \right) \cdot (386.3 - 0.12 \frac{\Pi^2}{2}) \cdot (55.8 \frac{\Pi}{4} - 1.99 \frac{\Pi^2}{4}) \cdot (2748.0 - 3470.2 \frac{\Pi}{5} + 1106.4 \frac{\Pi^2}{5})
\]

for \( 1 \leq \Pi \leq 1.5 \)

\[\cdots \cdots \cdots \cdots \cdots (5.28)\]
3. The analytical equations, to predict the surface bending stress number
generated in soil crust by emerging dicot seedlings, were found to be:

\[
\pi_{d4} = + \left[ \frac{96\pi}{1 - \pi_9} \sum_{n=1}^{\infty} \frac{\pi_8}{n^2} \right] + \left[ \frac{96\pi}{1 - \pi_9} \sum_{n=1}^{\infty} \frac{\pi_8}{n^2} \right] + \left[ \frac{384}{\pi} \sum_{m=1}^{\infty} \frac{\pi_8}{n^2} \right] \]

\[
\left\{ \frac{m\sin\left( m \pi \pi_9 / \pi_8 \right) \cos\left( 2m\pi_11 \right) }{n\sin(n\pi_1.5 / \pi_8) \cos\left( 2n\pi_12 \right) } \right\} \frac{1}{\pi_9} \left\{ \pi_9^{n^2} + 12 \left( \pi_{14}\pi_{10}/\pi_9^2 \right) (1 - \pi_13^2) \right\} \]

\[
\left\{ \cos(2m\pi_11) \cos(2n\pi_12) \right\} \}
\]

\[
\pi_{d3} = + \left[ \frac{96\pi}{1 - \pi_9} \sum_{n=1}^{\infty} \frac{\pi_8}{n^2} \right] + \left[ \frac{96\pi}{1 - \pi_9} \sum_{n=1}^{\infty} \frac{\pi_8}{n^2} \right] + \left[ \frac{384}{\pi} \sum_{m=1}^{\infty} \frac{\pi_8}{n^2} \right] \]

\[
\left\{ \frac{m\sin\left( m \pi \pi_9 / \pi_8 \right) \cos\left( 2m\pi_11 \right) }{n\sin(n\pi_1.5 / \pi_8) \cos\left( 2n\pi_12 \right) } \right\} \frac{1}{\pi_9} \left\{ \pi_9^{n^2} + 12 \left( \pi_{14}\pi_{10}/\pi_9^2 \right) (1 - \pi_13^2) \right\} \]

\[
\left\{ \cos(2m\pi_11) \cos(2n\pi_12) \right\} \}
\]

\[
\pi_9^{n^2} + 12 \left( \pi_{14}\pi_{10}/\pi_9^2 \right) (1 - \pi_13^2) \}
\]

\[
\left[ \pi_9^{n^2} + 12 \left( \pi_{14}\pi_{10}/\pi_9^2 \right) (1 - \pi_13^2) \right]\}
\]

\[
\cos(2m\pi_11) \cos(2n\pi_12) \}
\]

\[
\left[ \pi_9^{n^2} + 12 \left( \pi_{14}\pi_{10}/\pi_9^2 \right) (1 - \pi_13^2) \right]\}
\]
4. Soil moistures near field capacity at the time of planting are more favorable. In dry soils seedlings may never develop required seedling emergence force.

5. Closer seed spacing down the row causes increased bending stresses directly above the seedling therefore helping in increased seedling emergence in crusted soils.

6. The results of this study support the technique of soaking the seeds before planting to speed emergence time in crusted soils. Further investigations are needed to determine the time of soaking so that seeds will not be mechanically damaged by mechanical planters. Use of pneumatic type planters may be more appropriate.
CHAPTER 9

SUGGESTIONS FOR FURTHER STUDY

1. Effects of environmental and soil characteristic factors on mechanical properties of soil crust should be evaluated.

2. The seedling emergence force study should be extended to other soybean varieties and small-seeded crops such as tomatoes, sugarbeets.

3. A portable force transducer for field measurement of required seedling emergence force should be designed and developed.

4. The possibility of utilizing these results to breed plants with high emergence force capabilities should be investigated.

5. Further investigations are needed to determine any possible relationship between retention time for the seeds in water and seed damage by mechanical planters. The feasibility of pneumatic type planters should be considered relative to the need for planting high moisture seed with a minimum of mechanical damage.

6. A mathematical model could be established for the soil crust strength.

7. The bending stress study should be extended to include viscoelastic behaviour of soil crust and subsoil, and to include thermal stresses which cause shrinkage cracks in soil crusts.

8. Analytical predictions (Chapter 7) should be verified experimentally.
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APPENDIX A
MECHANICAL ANALYSIS OF CROSBY SILTLOAM SOIL

Minerological composition of crosby siltloam soil

Illite = 22%  Vermiculite = 58%
Quartz = 19%  Kaolinite = 1%

Chemical analysis of crosby silt loam soil

<table>
<thead>
<tr>
<th></th>
<th></th>
<th>Exchangeable cations:</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH, 1:1(H2O)</td>
<td>7.1</td>
<td>H  2.4 meq/100g</td>
</tr>
<tr>
<td>Total carbon</td>
<td>1.48%</td>
<td>Ca 13.4 meq/100g</td>
</tr>
<tr>
<td>calcite</td>
<td>0.7%</td>
<td>Mg 3.6 meq/100g</td>
</tr>
<tr>
<td>dolomite</td>
<td>0.3%</td>
<td>K 0.3 meq/100g</td>
</tr>
<tr>
<td>CaCO3 equivalent</td>
<td>1.0%</td>
<td>Total 19.7 meq/100g</td>
</tr>
<tr>
<td>pH, 1:2(CaCl2)</td>
<td>6.7</td>
<td></td>
</tr>
<tr>
<td>Sum of bases</td>
<td>17.3 meq/100g</td>
<td></td>
</tr>
</tbody>
</table>

Mechanical analysis of crosby silt loam soil

<table>
<thead>
<tr>
<th>Soil texture</th>
<th>Classification</th>
<th>Particle size mm</th>
<th>Particle size distribution %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Textural fraction</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sand</td>
<td>Very coarse</td>
<td>1 - 2</td>
<td>0.90</td>
</tr>
<tr>
<td></td>
<td>Coarse</td>
<td>0.5 - 1</td>
<td>2.40</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>0.25 - 0.5</td>
<td>2.70</td>
</tr>
<tr>
<td></td>
<td>Fine</td>
<td>0.1 - 0.25</td>
<td>8.00</td>
</tr>
<tr>
<td></td>
<td>Very fine</td>
<td>0.05 - 0.1</td>
<td>4.70</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>0.05 - 2</td>
<td>18.70</td>
</tr>
<tr>
<td>Silt</td>
<td>Fine</td>
<td>0.002 - 0.20</td>
<td>44.00</td>
</tr>
<tr>
<td></td>
<td>Coarse</td>
<td>0.02 - 0.50</td>
<td>14.40</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>0.002 - 0.50</td>
<td>58.40</td>
</tr>
<tr>
<td>Clay</td>
<td>Fine</td>
<td>0.0002</td>
<td>8.20</td>
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<tr>
<td></td>
<td>Coarse</td>
<td>0.0002 - 0.002</td>
<td>14.70</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>0.002</td>
<td>22.90</td>
</tr>
</tbody>
</table>

*USDA classification.

Analysis was conducted by Soil Characterization Laboratory, OSU.
Note: The soil was silt loam soil based upon textural triangle classification.
Moisture equivalent curve for Crosby silt loam soil.
APPENDIX C

MEAN EMERGENCE SOYBEAN SEEDLING FORCE NUMBER AT VARYING MOISTURE INDICES

Time index : 1.00
Mean seed diameter : 0.642 cm
Seed mass : 0.2 g
Internal seed energy : $2.471 \times 10^7$ J/kg
Ambient temperature : 26°C
Soil impedance : 660 kPa

<table>
<thead>
<tr>
<th>Seed moisture % db</th>
<th>Seedling force number, $x 10^{-14}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Soil moisture, % db</td>
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<tr>
<td>8.0</td>
<td>-</td>
</tr>
<tr>
<td>12.0</td>
<td>-</td>
</tr>
<tr>
<td>14.5</td>
<td>388.02</td>
</tr>
<tr>
<td>20.0</td>
<td>-</td>
</tr>
<tr>
<td>25.0</td>
<td>-</td>
</tr>
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</table>
### APPENDIX D

**CRITICAL TIME AT VARYING MOISTURE INDICES**

- Mean seed diameter: 0.642 cm
- Seed mass: 0.2 g/seed
- Internal seed energy: $2.47 \times 10^7$ J/kg
- Ambient temperature: 26°C
- Soil impedance: 660 kPa

<table>
<thead>
<tr>
<th>Seed moisture % db</th>
<th>Critical time, hours</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Soil moisture, % db</td>
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<tr>
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<td>12</td>
</tr>
<tr>
<td>8.0</td>
<td></td>
</tr>
<tr>
<td>12.0</td>
<td></td>
</tr>
<tr>
<td>14.5</td>
<td>131.0</td>
</tr>
<tr>
<td>20.0</td>
<td></td>
</tr>
<tr>
<td>25.0</td>
<td></td>
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APPENDIX E

Observed and predicted values of critical time and seedling force number.

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<thead>
<tr>
<th>Z</th>
<th>$Y_1$</th>
<th>$X_1$</th>
<th>$K$</th>
<th>Critical time</th>
<th>Seedling force number ($\times 10^{-14}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>% db</td>
<td>% db</td>
<td></td>
<td>Observed</td>
<td>Predicted</td>
</tr>
<tr>
<td>.525</td>
<td>18.0</td>
<td>8.0</td>
<td>1.0</td>
<td>113.0</td>
<td>113.8</td>
</tr>
<tr>
<td>.525</td>
<td>18.0</td>
<td>12.0</td>
<td>1.0</td>
<td>108.0</td>
<td>98.5</td>
</tr>
<tr>
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<td>14.5</td>
<td>1.0</td>
<td>91.5</td>
<td>92.1</td>
</tr>
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<td>.525</td>
<td>18.0</td>
<td>20.0</td>
<td>1.0</td>
<td>82.0</td>
<td>82.1</td>
</tr>
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<td>25.0</td>
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<td>75.8</td>
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<td>14.5</td>
<td>1.0</td>
<td>131.0</td>
<td>134.0</td>
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<td>15.0</td>
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<td>1.0</td>
<td>105.0</td>
<td>109.0</td>
</tr>
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<td>.525</td>
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<td>1.0</td>
<td>91.5</td>
<td>92.1</td>
</tr>
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<td>1.0</td>
<td>75.0</td>
<td>79.8</td>
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<td>70.0</td>
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<td>89.3</td>
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<td>-</td>
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</tr>
<tr>
<td>.525</td>
<td>18.0</td>
<td>14.5</td>
<td>0.4</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>.525</td>
<td>18.0</td>
<td>14.5</td>
<td>0.5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>.525</td>
<td>18.0</td>
<td>14.5</td>
<td>0.6</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>.525</td>
<td>18.0</td>
<td>14.5</td>
<td>0.7</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>.525</td>
<td>18.0</td>
<td>14.5</td>
<td>0.8</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>.525</td>
<td>18.0</td>
<td>14.5</td>
<td>0.9</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

1 Using equation 5.26 and at $C_1 = 660$ kPa
2 Using equation 5.27 and 5.28, and at $C_1 = 660$ kPa
APPENDIX F

Data on hypocotyl diameter of soybean seedling

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Cone index (Kg/cm²)</th>
<th>Hypocotyl diameter (cm)</th>
<th>Std. dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>1.124</td>
<td>0.1975</td>
<td>0.0028</td>
</tr>
<tr>
<td>20</td>
<td>1.124</td>
<td>0.3350</td>
<td>0.0013</td>
</tr>
<tr>
<td>26</td>
<td>1.124</td>
<td>0.3950</td>
<td>0.0090</td>
</tr>
<tr>
<td>32</td>
<td>1.124</td>
<td>0.3835</td>
<td>0.0045</td>
</tr>
<tr>
<td>15</td>
<td>2.249</td>
<td>0.2175</td>
<td>0.0021</td>
</tr>
<tr>
<td>20</td>
<td>2.249</td>
<td>0.3675</td>
<td>0.0022</td>
</tr>
<tr>
<td>26</td>
<td>2.249</td>
<td>0.4200</td>
<td>0.0023</td>
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<td>32</td>
<td>2.249</td>
<td>0.4003</td>
<td>0.0043</td>
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<td>15</td>
<td>4.499</td>
<td>0.2770</td>
<td>0.0045</td>
</tr>
<tr>
<td>20</td>
<td>4.499</td>
<td>0.4360</td>
<td>0.0013</td>
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<tr>
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<td>0.5160</td>
<td>0.0064</td>
</tr>
<tr>
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<td>4.499</td>
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<td>0.0073</td>
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<td>0.0028</td>
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<td>6.749</td>
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<td>0.0015</td>
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<td>26</td>
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<td>0.0053</td>
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<tr>
<td>32</td>
<td>6.749</td>
<td>0.5650</td>
<td>0.0030</td>
</tr>
</tbody>
</table>

Note: Mean of 4 observations.
APPENDIX G

MODULUS OF RUPTURE OF SOIL CRUST

Chart speed : 20 cm/hour
Load cell sensitivity : 5 kgf full scale deflection
Loading probe speed : 0.5 cm/hour
Soil : crosby silt loam soil
Average aggregate size : 0.265 cm
Rainfall intensity : 3.75 cm/hour
Total rainfall : 2.5 cm
Radiation intensity : 390 cal/cm²-day for 5 days.

<table>
<thead>
<tr>
<th>Average thickness</th>
<th>Length</th>
<th>Width</th>
<th>Load to break the slab</th>
<th>Modulus of rupture, ( s = \frac{3FL}{2bd^2} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( d ) cm</td>
<td>( L ) cm</td>
<td>( b ) cm</td>
<td>( F ) kgf</td>
<td>( \text{kgf/cm}^2 )</td>
</tr>
<tr>
<td>0.91</td>
<td>3.25</td>
<td>5.0</td>
<td>10.85</td>
<td>12.77</td>
</tr>
<tr>
<td>0.90</td>
<td>3.25</td>
<td>2.8</td>
<td>5.45</td>
<td>11.72</td>
</tr>
<tr>
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<td>3.8</td>
<td>12.08</td>
<td>11.92</td>
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<td>0.89</td>
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<td>5.0</td>
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<td>4.50</td>
<td>5.0</td>
<td>6.01</td>
<td>12.37</td>
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<td>5.0</td>
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<td>3.25</td>
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<td>11.99</td>
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<td>0.91</td>
<td>4.50</td>
<td>5.0</td>
<td>7.39</td>
<td>12.04</td>
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</tbody>
</table>

Mean \( \quad 12.09 \)

Std. dev. \( \quad 0.33 \)
## Appendix H. Bulk density of soil crust using saran solution.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Weight of soil crust sample $g$</th>
<th>Weight of coated crust sample in air $g$</th>
<th>Weight of coated crust sample in water $g$</th>
<th>Weight of plastic coat $g$</th>
<th>Volume of plastic coat $cm^3$</th>
<th>Volume of coated sample $cm^3$</th>
<th>Bulk density of coated sample $g/cm^3$</th>
<th>Bulk density of soil crust $g/cm^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>crust</td>
<td>72.25</td>
<td>73.88</td>
<td>29.11</td>
<td>1.63</td>
<td>1.25</td>
<td>44.77</td>
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<td>1.66</td>
</tr>
<tr>
<td>crust</td>
<td>14.92</td>
<td>15.26</td>
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<td>28.44</td>
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<td>1.65</td>
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<tr>
<td>sub-soil</td>
<td>18.57</td>
<td>18.99</td>
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<td>0.32</td>
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<td>2.28</td>
<td>85.06</td>
<td>1.57</td>
<td>1.58</td>
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</tbody>
</table>

Moisture content of soil crust = 6.1% db.
Moisture content of sub-soil = 12.0% db.
Specific gravity of saran solution = 1.3

Radiation treatment = 390 cal/cm²-day for 5 days.
Rainfall treatment = 3.75 cm/day for a total rainfall of 2.5 cm.
### APPENDIX I

**BULK DENSITY VERSUS SOIL SAMPLE THICKNESS DATA**

<table>
<thead>
<tr>
<th>Measured average thickness cm</th>
<th>Area of sample cm²</th>
<th>Volume of sample cm³</th>
<th>Calculated thickness cm</th>
<th>Bulk density of soil sample g/cm³</th>
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</thead>
<tbody>
<tr>
<td>a</td>
<td>b</td>
<td>c</td>
<td>d</td>
<td>e</td>
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<tr>
<td>1.19</td>
<td>42.45</td>
<td>54.16</td>
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<tr>
<td>4.58</td>
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<td>3.99</td>
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<tr>
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<td>37.26</td>
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<td>12.39</td>
<td>23.36</td>
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<tr>
<td>4.32</td>
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<td>45.30</td>
<td>4.18</td>
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<tr>
<td>0.75</td>
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<td>-</td>
<td>-</td>
<td>1.63</td>
</tr>
</tbody>
</table>

*a* Mean of thickness at 4 locations on the soil sample.

*b* Area of the soil sample was measured by planimeter.

*c* Volume of soil sample was measured by Archimedes's principle.

*d* Calculated thickness was obtained from b and c.

*e* Bulk density of soil sample was determined by Saran immersion technique described in chapter 6.
APPENDIX J

POISSON'S RATIO AND MODULUS OF ELASTICITY OF SOIL CRUST (CROSBY SILT LOAM SOIL)

Poisson's ratio data

<table>
<thead>
<tr>
<th>Load, $P_1$ (kgf)</th>
<th>Stress, $\sigma$ (kgf/cm)</th>
<th>Axial strain, $\varepsilon_a$ (micro-cm/cm)</th>
<th>Transverse strain, $\varepsilon_t$ (micro-cm/cm)</th>
<th>$V = \varepsilon_t / \varepsilon_a$</th>
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</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>0.1</td>
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<td>0.40405</td>
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<td>10.0</td>
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</table>

Mean 0.236
Std. dev. 0.017

Modulus of elasticity data

<table>
<thead>
<tr>
<th>Load, $P_1$ (kgf)</th>
<th>Stress, $\sigma$ (kgf/cm²)</th>
<th>Strain, (micro-cm/cm)</th>
</tr>
</thead>
<tbody>
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<td></td>
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<tr>
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<tr>
<td>0.10</td>
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<tr>
<td>0.80</td>
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</tbody>
</table>

Note: Soil sample size = 6 x 3.25 x 1.53 cm
SUMMARY

STRESSES GENERATED IN SOIL CRUST BY EMERGING DICOT SEEDLINGS

By

Megh-Raj Goyal, Ph.D.

The Ohio State University, 1979

Professor Gordon L. Nelson, Advisor

Production of crops such as corn, soybeans, grain sorghum, cereals, sugarbeets, mustard, sunflower, guar, grasses, and vegetables can be adversely affected by failures to obtain good emergence due to soil crusting. It is assumed that emergence through a crusted soil would occur if the maximum surface bending stress in soil crust generated by an emerging seedling is greater than the soil crust strength. Williams soybean variety and a crosby silt loam soil were used in this study. The objectives of this study were to (1) Experimentally establish the relationships to predict soybean seedling emergence force as a function of seed and soil moistures and seed characteristic factors. (2) Develop generalized prediction equations for the seedling force number and critical time (Time at which seedling attains its maximum force) as a function of environmental and seed characteristic factors using dimensionless parameters. (3) Experimentally evaluate the effects of environmental temperature and soil impedance on soybean hypocotyl diameter. (4) Develop an analysis to predict the state of soil crust surface bending stresses generated by emerging dicot seedlings using thin plate theory and dimensional analysis. (5) Suggest management techniques to promote seedling emergence in crusted soils based upon these studies. The generalized prediction equations for the 'Critical Force Time' and 'Seedling Force Number' were found to be:
\[ \frac{t_c}{1072} = \left[ \frac{\theta_a - \theta_l}{\theta_m - \theta_l} \right]^{-0.1202} \cdot \left[ x_1 \right]^{-0.3563} \cdot \left[ y_1 \right]^{-0.9251} \cdot \left[ \frac{c_1 d^3}{J_1 E_1 m_1} \right]^{-0.1073} \]

\[ \Pi_{d1} = (0.24370 \times 10^{-21}) \cdot (-294.2 + 224.7 \omega_2 - 2002.0 \omega_2^2) \cdot (386.3 - 0.12 \omega_3^2) \cdot (55.8 \omega_4 - 1.99 \omega_4^2) \cdot (-149.5 \omega_5 + 496.9 \omega_5^2) \]

for \( 0 \leq \omega_5 \leq 1.0 \)

Where \( \Pi_{d1} \) = Seedling force number, \( \Pi_2 \) = Ambient temperature index = \( (\theta_a - \theta_l)/(\theta_m - \theta_l) \), \( \Pi_3 \) = Soil moisture = \( x_1 \), \( \Pi_4 \) = Seed moisture = \( y_1 \), \( \Pi_5 \) = Time index = \( t/t_c \), and \( t_c \) = Critical time.

Hypocotyl diameter increased with increased soil impedance above the developing seedling at constant temperature. For a given soil impedance, maximum diameter occurred at an temperatures of 26°C.

The results of this study support the technique of soaking the seeds before planting to speed emergence time in crusted soils. Soil moistures near field capacity at the time of planting are more favorable. In dry soils seedlings may never develop required seedling emergence force.

A technique was developed to evaluate soil crust mechanical properties including Poisson’s ratio and Young’s modulus. The technique consisted of evaluating surface strains on a soil crust sample when subjected to simple bending test. Surface strains were evaluated using electrical strain gages bonded to the soil crust sample. The saran immersion technique was found to be successful for evaluating the bulk density of soil crust.

An analysis was conducted to predict soil crust bending stresses directly above the emerging seedlings. It was found: (1) The bending stress number, \( \sigma_{yy} h^2/P \), was positively correlated with the ratio of down-the-row seed spacing to hypocotyl radius, (2) The bending stress number was negatively correlated with the ratio of down-the-row seed spacing to soil crust thickness and with the index of ratio of uncrusted soil and crust moduli.
Based upon these results, management techniques were identified to promote seedling emergence in crusted soils.