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I am submitting herewith a dissertation written by Hadagali Purnapragnachar entitled "Effect of Soil Moisture Tension and Density Upon Corn Seedling Emergence." I recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Agricultural Plant and Soil Science.

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EFFECT OF SOIL MOISTURE TENSION AND DENSITY UPON CORN SEEDLING EMERGENCE

A Dissertation

Presented to

the Graduate Council of

The University of Tennessee

In Partial Fulfillment

of the Requirements for the Degree

Doctor of Philosophy

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by

Hadagali Purnapragnachar

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TABLE OF CONTENTS

CHAPTER		PAGE
I.	INTRODUCTION	1
II.	REVIEW OF LITERATURE	3
	Effect of Soil Physical Factors on Germination of Seed	3
	Depth of Sowing and Seedling Emergence	6
	Effect of Exchangeable Cations and Moisture Content on Seedling Emergence . . .	7
	Effect of Soil Moisture on Germination of Seed	10
III.	MATERIALS AND METHODS	17
IV.	RESULTS AND DISCUSSION	24
	Forces Involved in Seedling Emergence	24
	Energies Involved in Seedling Emergence	36
	Computations of Pressures Involved in Seedling Emergence	44
V.	SUMMARY AND CONCLUSIONS	51
LITERATURE CITED		54

LIST OF TABLES

TABLE		PAGE
1.	Physical Characteristics of Sequatchie Sandy Loam	25
2.	Per Cent Moisture Retained by Sequatchie Sandy Loam at Different Soil Moisture Tensions	26
3.	The Maximum Time and Force Required for Seedling Emergence at Different Moisture Tensions and Bulk Densities of Sequatchie Sandy Loam	38
4.	Energies Exerted by Seedling at Different Soil Moisture Tensions and Bulk Densities for Sequatchie Sandy Loam	42
5.	Pressures Exerted by Seedling for Emergence at Different Moisture Tensions and Bulk Densities of Sequatchie Sandy Loam	47

LIST OF FIGURES

FIGURE		PAGE
1.	Arrangement of the Apparatus for Seedling Emergence	18
2.	Balance Pan Showing Seedling in the Process of Emergence	19
3.	The Arrangement of the Apparatus for Determining the Force Exerted by the Seedling During Emergence Through the Soil	22
4.	Moisture Release Curve of Sequatchie Sandy Loam . .	27
5.	Force Exerted by Seedling at Different Moisture Tensions of Sequatchie Sandy Loam at Bulk Density of 1.1 gm./cm.^{3}	30
6.	Relationship Between Time and Force Exerted by Seedling at Different Moisture Tensions at Bulk Density of 1.1 gm./cm.^{3}	31
7.	Force Exerted by Seedling at Different Moisture Tensions of Sequatchie Sandy Loam at Bulk Density of 1.2 gm./cm.^{3}	33
8.	Relationship Between Time and Force Exerted by Seedling at Different Moisture Tensions at Bulk Density of 1.2 gm./cm.^{3}	34

FIGURE PAGE

9. Relationship Between Force Exerted by the Seedling and Time at Bulk Densities of 1.1, 1.2 and 1.3 gm./cm.^{3} 37

10. Relationship Between Force Exerted by Seedling With Time at Bulk Densities of 1.1 and 1.2 gm./cm.^{3} 38

11. Relationship Between Seedling Length and Time . . 39

12. Energy exerted by Seedling at Different Moisture Tensions and Bulk Densities for Sequatchie Sandy Loam 43

13. Pressure Distribution Over the Tip of the Seedling 45

14. Pressure Exerted by Seedling at Different Moisture Tensions and Bulk Densities for Sequatchie Sandy Loam 48

CHAPTER I

INTRODUCTION

Seed germination in the field is of prime importance for successful development of a crop. Various factors like the moisture content in the soil, the soil texture and structure, the type of soil clay, the ionic environment and other factors influence the germination and emergence of a seedling from the soil. The factors pertaining to the seed itself like type of seed, its vigor, the condition of the seed being free from diseases and pests, etc., also influence the germination and stand of a crop.

Although some of the above factors have been recognized to have their individualistic influence on the germination of seeds, not much comprehensive work has been done to test their combined effects, under conditions simulating those of the field.

The total water potential is the quantity normally associated with the total soil moisture. The total potential of soil water can be considered as having the following three components, i.e., $\Phi = T + \pi + Z$ where T is the suction component or capillary potential which includes the consequences of all the physical and colloidal attraction of the main soil mass for soil water. This has been termed as

matric potential by Taylor et al., (54) as this quantity included phenomena associated with capillarity as well as surface adsorption phenomina. π is the osmotic potential which takes into account all dissolved material in the soil and is usually called osmotic pressure (43). Z is defined as the gravitational potential resulting from the vertical position of the moisture under consideration. Each of the above components can be varied independently of one another and can be measured conveniently in terms of units of length. Φ represents the amount of work necessary to remove unit weight (or volume) of pure salt free water from a large mass of soil water having the matric potential due to attraction of the soil matrix for water. In the case of a biological organism, the site of absorption of water in a soil system is not influenced greatly by the gravitational potential. Hence it can be taken as zero. Therefore, the total potential has now only two components, i.e., the matric potential and the osmotic potential (13).

As a young seedling forces its way upward through a soil formation, mechanical work is done. The energy relationships involved in the emergence of a corn seed as influenced by soil texture, soil density, and moisture, alone and in combination have been studied in these investigations.

CHAPTER II

REVIEW OF LITERATURE

There are a number of factors prevailing in the soil as well as that pertaining to a seed itself that condition the germination of seeds. The physical condition, the ionic environment, the moisture level, the ravages of insects or pathogens, temperature, and aeration of the soil are some of the influences that may limit the germination of seeds. While recognizing that any one of these factors may be decisive in obtaining a stand of plants, the present review is confined to some of the factors cited above.

Effect of Soil Physical Factors on the Germination of the Seed

Experiments conducted by Carnes (11) to study the formation of soil crusts, their strength and effect on the injury to cotton stands, indicated that the modulus of rupture was a function of pore space and that a more compact soil afforded a firm seed bed for cotton, and a firm footing for the plant to break through. Barmington (6) studied the physical factors of soil affecting beet seedling emergence. He concluded that a correlation existed between type of equipment used, the firmness of the soil after using various

tools, the moisture held in the seed zone and the emergence of seedlings. Baird, et al. (5) indicated that the use of chemical additives like VAMA (partial calcium salt of vinyl acetate-maleic acid) and HPAN (sodium salt of hydrolysed polyacronitrile) incorporated to various depths at rates of 0 to 2 per cent of soil weight, had an effect of increasing emergence of beet seedlings in two out of three field trials. However, when they were applied as dilute water solutions, there was no effect on the emergence of beet seedlings. Slater and Rodriguez (51) reported that stability of aggregates to slaking as determined by wet sieve analysis failed to account for differences in structural quality between naturally stable and chemically stabilized Christiana silt loam. The treated and untreated soils were equally resistant to slaking, but permeability and seed germination were better in the treated soil. Hanks and Thorp (30) tested the emergence of wheat seedlings on three soils varying in texture from a silty clay loam to a fine sandy loam with different combinations of moisture, bulk density, oxygen diffusion rate and crust strength. It was found that the ultimate seedling emergence was nearly the same when the moisture content was maintained between field capacity and the wilting percentage, if other factors were optimum for maximum seedling emergence. It was also observed that bulk density was related indirectly to

seedling emergence in that any change in bulk density changed other factors such as oxygen diffusion rate and soil crust strength. Hanks and Thorp (31) further reported that at constant soil moisture content of wheat, grain sorghum and soybean, seedling emergence was decreased with increasing crust strength. Flocker et al. (24) found that compacting the soil to a certain density increased the percentage of germination of tomato seeds, but that compression beyond a certain point seriously reduced the percentage of germination. Compacting the soil increased the time required for seedlings to emerge. Adams et al. (1) reported that, in field plots packed deliberately, corn germination was slowed down with consequent delayed maturity. Hanks (29) further showed that seedling emergence was limited when the soil dried because the crust strength was consequently increased. Soil crusting was shown to be related to bulk density by a relationship of the form, crust strength = KA^d where K and A were constants and d was bulk density. Johnson and Buchele (38) showed that, as granular size increased and compactive effect of soil decreased, the overall rate of drying increased and total emergence of corn was less complete.

Laboratory experiments conducted by Stout et al. (53) with regard to the effect of soil compaction on seedling emergence under simulated field conditions indicated that

pressures in excess of one-half psi applied at the surface usually suppressed emergence of beet, bean and corn seedlings. However, pressures of five and ten psi applied at seed level improved emergence. Bennett et al. (8) reported that seedling emergence was negatively correlated with the crust strength and positively correlated with the moisture content of the top three inches of the soil. Concerning the soil strength and seedling emergence relation, Parker and Taylor (46) reported that, with four of six soils tested, light compression apparently increased the emergence of grain sorghum seedlings, but emergence was progressively decreased by increases in soil strength above three bars. No emergence was seen when soil strength exceeded thirteen bars in Miles soil. Only a minor effect of planting depth in the relation between grain sorghum seedling emergence and soil strength was noticed.

Depth of Sowing and Seedling Emergence

Hudspeth and Jones (35) found that on the high plains, the optimum covering depth for cotton seed for best emergence and yield was one to two inches. McGinnies (42) reported that the use of furrows two to four inches deep significantly increased soil moisture available for seed germination on a range soil by reducing the rate of moisture losses. Seedling establishment was improved by using a four

inch deep furrow. Weigand (58) concluded that the moisture distribution with depth was found to be parabolic. The moisture content at a given depth in the seed zone was expressed by $\theta = at^{-b}$ where θ was the moisture percentage, t was the time in days since irrigation, "a" was the moisture content at a given depth one day after irrigation and "b" was the slope of the plot of moisture content versus time on log-log co-ordinates. It was also found that the equation could be used for estimating moisture content for periods longer than those studied and for calculating the rate at which the moisture content of the soil at a particular depth was changing.

Effect of Exchangeable Cations and Moisture Content on Seedling Emergence

As early as 1898, Stewart (52) reported that increasing salt concentration decreased the percentage of germination. He found the cereals would be a much surer crop on alkali soil than the legumes would be. Buffum (10) summarized the effect of alkali salts on germination of wheat, rye and white sweet clover. It was observed that, of the alkali salts most abundant in the arid regions, those that had the greatest detrimental effects on germination in order were sodium carbonate, sodium chloride, sodium sulfate and magnesium sulfate. Harris (33) worked on the effect of

alkali salts in soils on the germination of wheat and sugar beet seeds. It was concluded that the period of germination of seeds was considerably lengthened by the presence of soluble salts in the soil. Shive (50) studied the effects of salt concentration (nitrates, carbonates, phosphates and chlorides of potassium, magnesium sulfate and calcium nitrate) on the germination of bean and corn seeds. It was seen, that the higher the concentration of solution added to the sand culture, the greater was the time required for germination. Parker and Oliver (47) indicated that the amount of injury that took place when fertilizers came into contact with seed depended on the kind and concentration of fertilizer salts. It was also found that the concentration of the fertilizer salts in solution was dependent upon the rate of application and the soil moisture level. No general relationship between relative tolerance (salt) of germinating seeds and the tolerance during later phases of growth was observed by Ayres and Hayward (4). Ayres (3) studied the germination as affected by soil moisture and salinity. He opined that the rate and/or percentage of germination might be affected by varying the soil moisture in a non-saline soil and also by varying the salinity in a soil at an initial constant moisture content. It was reported by the United States Salinity Laboratory Staff (57) that the germination of beans, beets, alfalfa and barley decreased

with increasing conductivity of saturation extract. Barley was salt tolerant at all stages although it was more sensitive at germination while beans was the most susceptible to the increasing conductivity of the soil extract. Olsen and Dreier (45) reported that unfavorable effects might be seen on germination of small grains with as low as ten pounds of nitrogen per acre adjacent to the seed during a period of low soil moisture. Guttay (26) showed that complete fertilizers used at rates of 100 pounds or more of nutrients per acre when placed in contact with wheat seed seriously delayed and hampered germination and emergence. Emergence of wheat was reduced and delayed when fertilizer was in contact with seed under dry as compared to moist conditions. Chapin and Smith (12) studied the germination of wheat at various levels of soil moisture as affected by application of fertilizers with moisture at field capacity caused delay in germination. If the fertilizers were placed in direct contact with the seed and if the soil moisture was at or near permanent wilting point, germination was reduced greatly or even prevented by heavy application of fertilizers. Cummins and Parks (16) observed that corn was (more less)? tolerant to higher salt concentration than was wheat. The nitrogen and potash fertilizers were more detrimental to germination than were the phosphate fertilizers. Allred and Ohlrogge (2) reported that free ammonia associated with

diammonium phosphate fertilizer was toxic to germinating corn when it was exposed to this environment for two days duri ng the initial stages of germination. Gasser (25) observed that the decrease in germination of kale or barley or wheat was caused by the increased osmotic pressure of the urea solution. Although some urea might have been hydrolysed in the seed, urea itself did not seem to be toxic. Sulfate was less damaging than nitrate and chloride, probably because the sulfate solution had lower osmotic pressures at equal NH_4 and K concentrations.

Effect of Soil Moisture on Germination of Seed

Doneen and MacGillivray (18), working on the germination of vegetable seeds as affected by different soil moisture conditions, reported that the germination at low soil moisture appeared not be correlated with the size of seeds. Seeds germinated more quickly at high soil moistures than at low. Probst (48) studied the influence of fertilizers, fertilizer placement, soil moisture content and soil type on the emergence of soybeans, and concluded that low soil moisture at planting, and 125 pounds of 0-20-0, or 0-0-20 in contact with seed did not significantly reduce emergence. In the absence of fertilizer or when the fertilizer was applied in bands, the difference in emergence due to content was not so pronounced except under field

conditions. The effect of osmotic pressure on water absorption and germination of alfalfa seeds was observed by Uhvites (56). With higher concentrations of sodium chloride or Mannitol, the germination was lower. In sodium chloride solution, the germination was almost inhibited at 12-15 atmospheres osmotic pressure. The hydration of seeds decreased as the concentration of substrate increased either with sodium chloride or Mannitol. Leach et al. (39) experimented on the influence of soil moisture on the emergence rate of sugar beet seed, and he found that decorticated sugar beet seeds germinated faster and showed a higher percentage of potential emergence than whole seed at low soil moistures. At high soil moisture there were only slight differences in rates of emergence between whole, decorticated and segmented beet seed.

Toole, et al. (55) indicated that, for best seed germination, moisture at near 60 per cent water holding capacity was injurious, but no significant difference in germination was found between 40 and 50 per cent of water holding capacity. Hunter and Erickson (37), studying the relation of seed germination to soil moisture, showed that a soil at 25° C should have a moisture tension of not more than 12.5 atmospheres for corn to germinate, 7.5 atmospheres for rice and 3.5 atmospheres for sugar beet seed to germinate. Delouche (17) concluded that moisture levels of 12-14

per cent were most favorable for water melon germination; corn and soybeans germinated best at 15 per cent moisture. Corn germination was least affected by various levels of moisture in the range of 6 to 21 per cent by weight; water melon germination was most affected by the variation in the soil moisture levels.

Collis-George and Sands (13) worked on the control of seed germination by moisture as a physical property. It was concluded that for all the species of seeds that were tried, an increase in suction produced a decrease in rate of germination until at 10 atmospheres tension when germination practically ceased. The moisture condition of the soils controlled the germination rate not only by means of the suction effect, but also in terms of hydraulic conductivity. A drier soil, having less ability to transmit water than a wetter soil, reduced the rate at which water could reach the seed, thus causing a consequent decline in the germination rate. They also further suggested that it was necessary to define the moisture characteristic as well as moisture content in germination experiments.

Dotzenko and Dean (19) reported that the germination of six alfalfa varieties decreased as the osmotic pressure of the solution increased. Dubetz et al. (21) expressed, regarding the effect of fertilizers and osmotic pressure on germination, that moisture levels of 18.85, 15.30, 11.75 per

cent soil moisture expressed on oven dry basis did not have any effect on germination percentage. Moisture levels in combination with nitrogen fertilizers reduced germination, and the reduction became progressively pronounced with decreasing moisture. Germination of sugar beets was significantly lowered in solutions having osmotic pressures exceeding four atmospheres. Eslik and Vogel (22) reported that emergence of western wheat grass and standard crested wheat seedlings was increased by holding the soil moisture at tensions above field capacity. Hoshino et al. (34) concluded, from studies on environmental factors affecting the seed germination and seedling growth of several pasture species, that the percentage of germination for all species decreased with increase in osmotic pressure and that there was no germination at twenty atmospheres. As for soil moisture deficiency, orchard grass and Ladino clover showed the most suppressive effect of high osmotic pressure. Dotzenko and Haus (20) worked on the selection of alfalfa lines for their ability to germinate under high osmotic pressures. They concluded that the ability to germinate at 12 atmospheres of osmotic pressure in a mannitol solution was heritable and varied with the different varieties tested. Collis-George and Sands (14) reported that oats and alfalfa both showed a significant decrease in germination rate on increasing the suction from 0 to 6 cm. water while perennial

type grass showed an increase in the rate over the same range.

With regard to the sorghum seed germination as affected by moisture and temperature, Evans et al. (23) observed that germination did not occur at the low moisture level which was slightly below the wilting percentage. Emergence at the medium moisture level was significantly less than it was at the high level (field capacity). Hudspeth and Taylor (36) observed that, with static medium to high available moisture level pressures of one psi on loose soil, significantly greater emergence through a depth of one-half inch loose soil, occurred at about one-third atmosphere soil moisture tension. Collis-George and Sands (15) compared the effects of the physical and chemical components of soil water energy on seed germination. It was seen that germination behavior did not support the hypothesis that matric and osmotic potentials had similar biological consequences because their free energy measurements are identical. The results supported a diffusion phenomenon hypothesis with movement of solute from the soil solution through the cell membranes so that the biological consequence was that of an internal "toxicity" rather than an osmotic "drought." For some osmotic systems, 100 cm., of matric potential was as effective as 10,000 cm. of osmotic potential in retarding seed germination rates. Hack (27)

tested the germination of tomato seeds at controlled soil moisture from 0.3 to 20 cm. Hg. Germination was slow and poor in the wetter treatments at 0.5 and 1 cm. Hg. and it was satisfactory at 2 cm. Seedlings appeared more rapidly at 2 cm. than at 20 cm. Hg. Sedgley (49) observed that the rate of germination of seeds was not influenced by small pressure potentials which, like matric potentials were a non-osmotic component of the total water potential. Experiments conducted by Lyles and Fanning (40) lead to the conclusions that moisture tension and/or soil salinity increased emergence time and decreased total emergence of sorghum seedlings. Manohar and Heydecker (41) investigated the effects of water potential on germination of pea seeds. It was found that a matric potential of 0.1 atmospheres had a surprisingly great effect on the rate of germination (though not on its percentage), considering that the diffusion pressure deficit of germinating peas seeds was still 2.6 atmospheres. They also concluded that the osmotic and matric potential might be theoretically equivalent but might differ in their effect on seed germination, largely because differences in the special systems involved tend to reduce the effect of osmotic and increase the effect of matric potentials. Yamanto (59) studied the relationship between seed germination and soil water content. It was observed that water contents of soils required for germination of

soybean seed were 1-2 per cent for beach sand, 8 per cent for sand derived from Lapilli, 12-13 per cent for arable soil, 25-26 per cent for grassland soil, 37-38 per cent for beech-forest soil and 65-67 per cent for moor peat. Germination rates were lower in beech-forest and moor soils than in the others. Soil water contents required for germinations were twice or two and a half times as much as the hygroscopic water contents. Harper and Benton (32) concluded that there was no simple relationship between germination and the tension on the available water, and that despite the high diffusion pressure gradient between seeds and substrate, such factors as mucilage, the size and the nature of the seed surface had marked influences on germination.

CHAPTER III

MATERIALS AND METHODS

A Sequatchie sandy loam was used in these studies. The soil samples were taken from the Main Experiment Station at Knoxville. Representative soil samples were drawn from a profile of 0-15.2 cm. (0-6") and ground to pass a 2 mm. sieve. The physical characteristics of the soil were determined according to the procedures of Black et al. (9).

As a preliminary to obtain seedlings for the experiment, corn seeds were placed in a cardboard framework in which two blotting papers were mounted. The cardboards and the blotting papers were held by two garden labels and rubber bands. In order to reduce the variation due to the seedling size and age, as uniform seedlings in shoot length as available and of same age (five days old) were selected. Uniform seeds of Dixie 29 hybrid were used.

A Sartorius balance was mounted in a wooden box of 66 cm. x 46 cm. x 61 cm. such that the balance scale was outside the box while the pan and the rest of the body were inside the box. The box was made light proof. A clamp stand was placed in the box to hold the soil sample box. The setup is indicated in Figures 1 and 2.

The seedling was mounted carefully without injuring

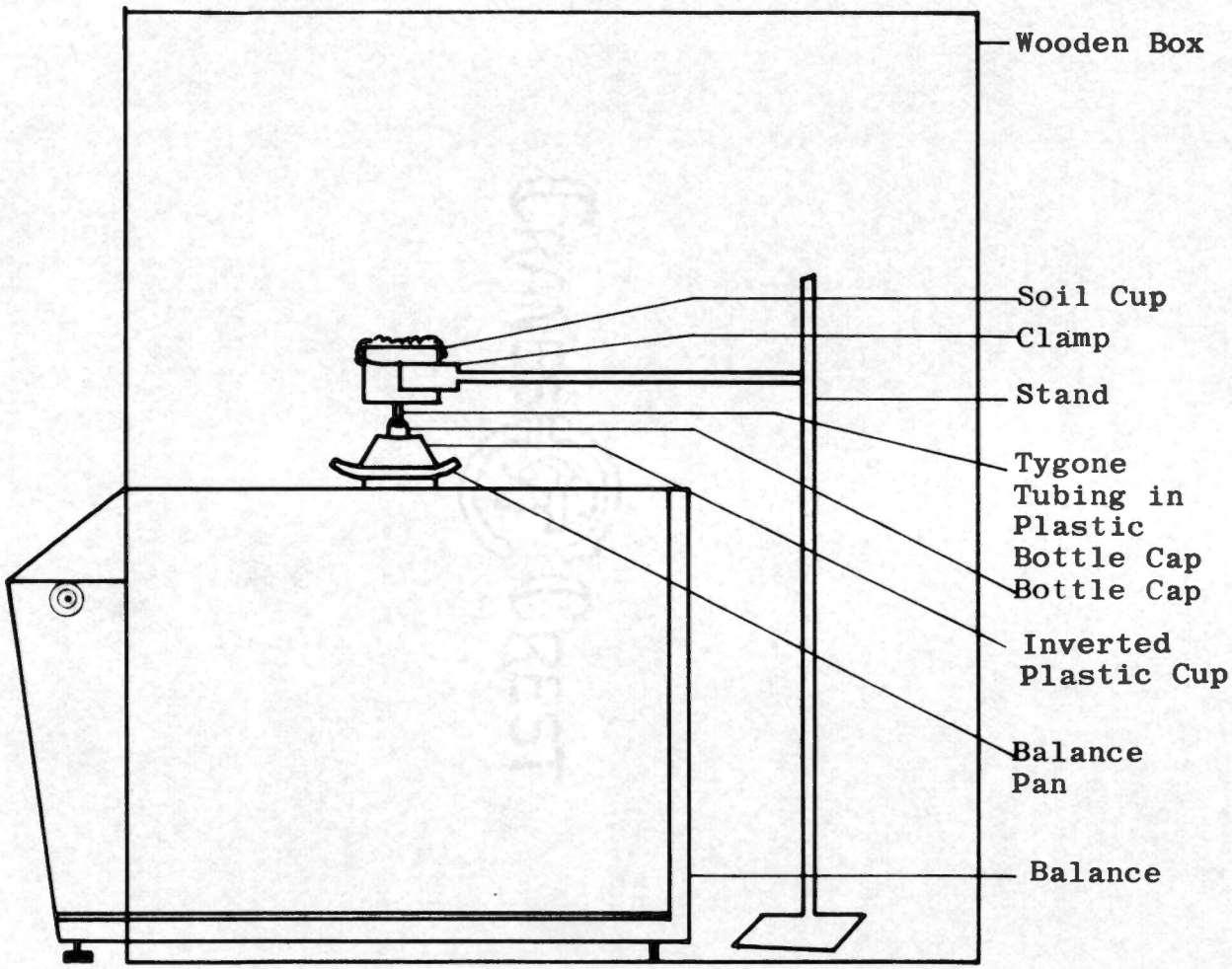


Figure 1. Arrangement of the apparatus for seedling emergence.

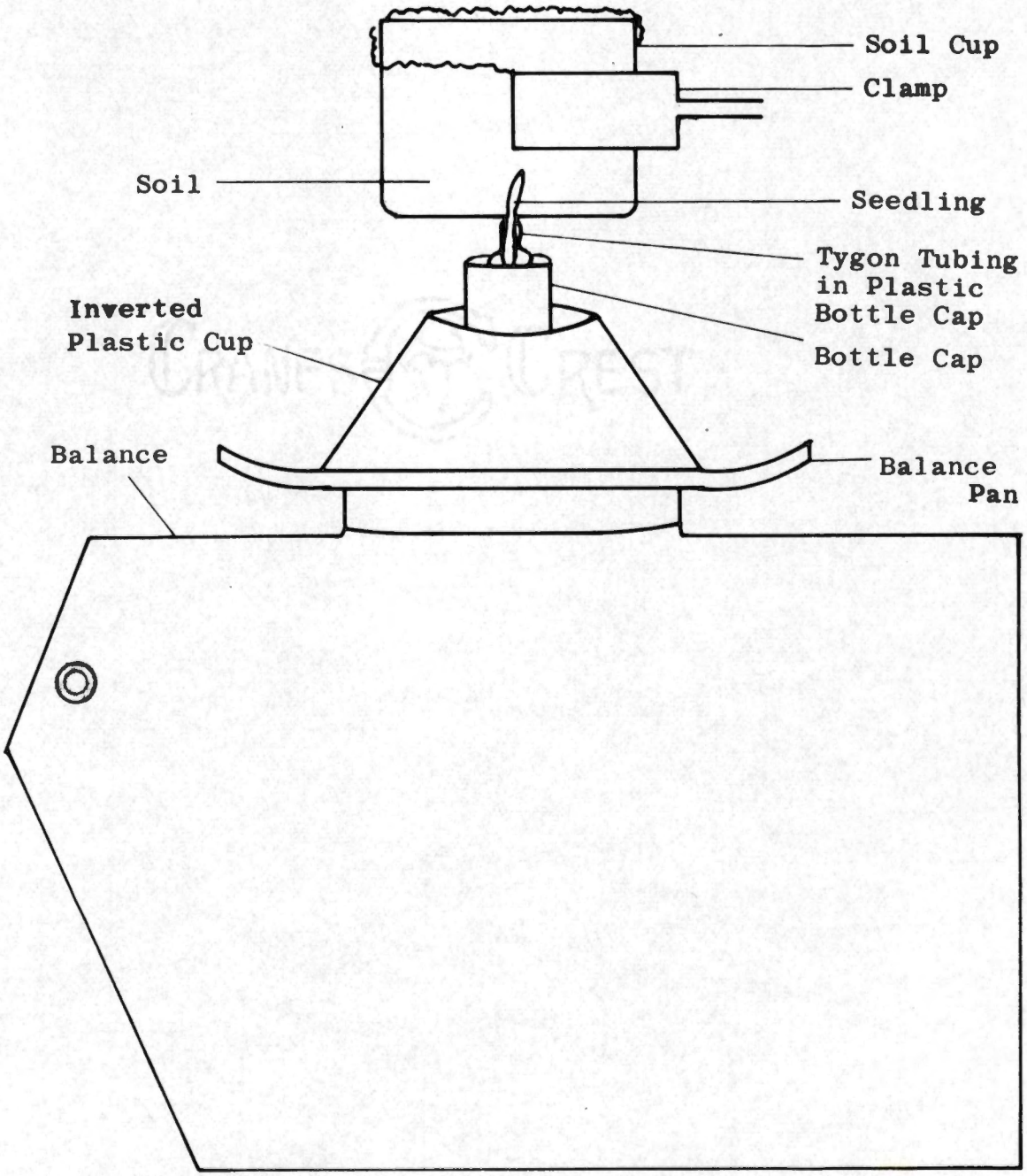


Figure 2. Balance pan showing seedling in the process of emergence.

the root in a small plastic bottle cap of 4 cm. diameter and 2 cm. height. The bottle cap was fixed to an inverted round plastic cup (9 cm. diameter and 5 cm. high) and was held securely with candle wax. Sand was used to mount the seedling. A small plastic bottle cap (2.5 cm. diameter) with a 5 mm. (outer diameter) tygon tube of 3 to 5 mm. length mounted in a 5 mm. center hole was placed over the seedling. This tygon tubing aided in directing the seedling into the soil column. The cap was then watered to supply moisture for the seedling growth during the entire period of its emergence through the soil.

The soil at the predetermined depth, bulk density and moisture content was prepared in an aluminum box of 64 mm. diameter and 44 mm. height. This had a hole of 5 mm. diameter at the center of the bottom. The soil sample having 60 cm. of water tension was obtained using the tension table. For a soil sample containing moisture at one atmosphere tension, the sample was first subjected to pressure in a pressure cooker using a porous plate. This soil was consolidated in the aluminum box using as much soil as necessary to attain the required depth (20 mm.) and bulk density. Other soil samples of moisture tensions beyond one atmosphere were prepared using a pressure membrane apparatus.

The soil in the aluminum cup with a plastic cover to minimize evaporation from the soil was mounted in the clamp

stand. The seedling was placed on the balance pan and the balance was adjusted to start at zero reading by putting additional weights on the pan. The small tygon tube was adjusted so that there was about 0.5 to 1 mm. distance between it and the opening of the hole in the bottom of the aluminum box.

As the seedling growth progressed through the soil, the reading on the balance dial increased with the increase in the force exerted by the seedling. The readings were either recorded periodically at 10 to 15 minute intervals manually or photographed by the Bolex movie camera using a time lapse technique every ten minutes. The readings on the film were read in a microfilm reader. A pocket watch was placed near the dial so that time could also be noted. A code label was placed below the dial of the balance to identify the sample in the microfilm readings. A photograph of the setup is shown in Figure 3. The determinations for each treatment were done in triplicate.

The rate of seedling growth with time was studied as follows: A known quantity of soil was compacted in a graduated cylinder with the seedling (just germinating) at the bottom. The cylinder was covered with a plastic sheet to reduce evaporation and also wrapped in a felt cloth, and kept slanting at about 20^{o} to the vertical. This made the seedling move along the side of the glass face as it

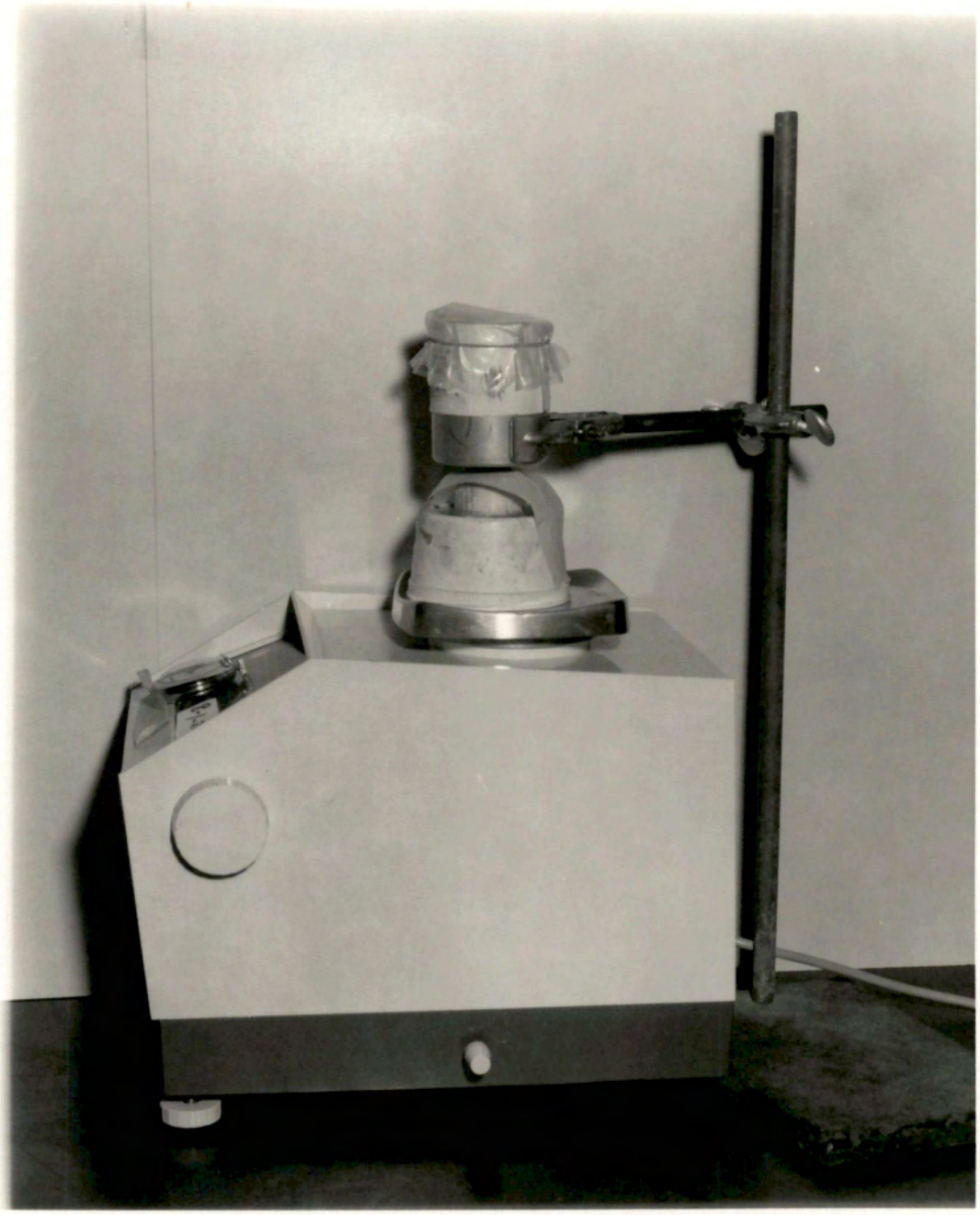


Figure 3. The arrangement of the apparatus for determining the force exerted by the seedling during emergence through the soil.

penetrated the soil column. The length of the seedling at different time intervals was recorded.

The energies involved in the germination of the seedling were calculated using the relationships of force and time and rate of growth and time of the seedling emergence.

CHAPTER IV

RESULTS AND DISCUSSION

The physical characteristics of Sequatchie sandy loam are presented in Table 1. The organic matter content was 1.34 per cent which can be considered normal for such soils. The soil contained 69.04 per cent sand, 20.51 per cent silt and 10.45 per cent clay. The mean bulk density was 1.29 gm./cm.^{3} with 22.06 per cent large pores and 28.30 per cent small pores. These characteristics give rise to a medium available water holding capacity of the soil (0.24 inches per inch) in the surface six inches.

Table 2 gives the moisture contents of the soil at different tensions. The high sand and low clay contents indicate also the reason for release of most of the moisture at lower soil moisture tensions, as about 50 per cent of moisture held is released below one bar tension. The moisture release curve (Figure 4) shows 18.6 per cent moisture at field capacity (0.30 bar tension) and 4.6 per cent moisture at wilting point (15 bars tension).

Forces Involved in Seedling Emergence

The maximum time required for emergence, the force exerted and the moisture per cent of the sample, at different bulk densities, are shown in Table 3.

Table 1. Physical characteristics of Sequatchie sandy loam

Organic matter	1.34 per cent
Sand	69.04 per cent
Silt	20.51 per cent
Clay	10.45 per cent
Large pores	22.06 per cent
Small pores	28.30 per cent
Bulk density	1.29 gm./cm.^{3}

NOTE: Depth of sample 0-6 inches.

Table 2. Per cent moisture retained by Sequatchie sandy loam at different soil moisture tensions

Soil moisture tension in bars	Per cent moisture by weight
0.059 (60 cm.)	28.5
0.30	18.6
0.60	12.5
1.0	12.3
3.0	7.7
5.0	6.9
7.0	6.2
9.0	5.5
15.0	4.6

NOTE: Depth of sample 0-6".

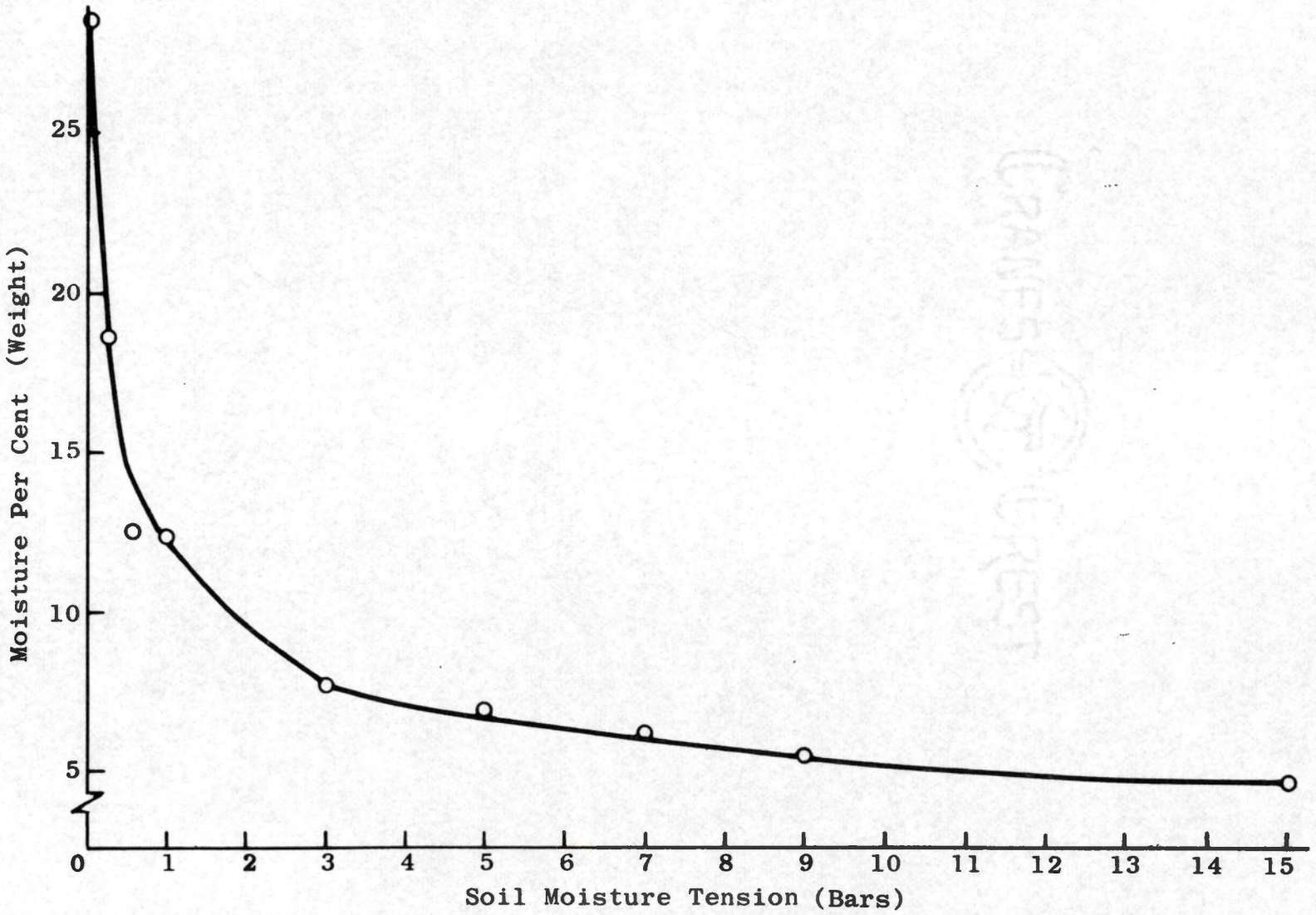


Figure 4. Moisture release curve of Sequatchie sandy loam.

Tarent moisture

Moisture tension in bars	Bulk density gm./cm.^{3}	II		Average		
		T: m:	Moisture per cent by weight	Time in minutes	Force gm.	Moisture per cent by weight
1.0	1.1		10.7	1111	65.1	12.3
3.0	1.1		8.0	957	37.8	7.8
5.0	1.1		6.0	697	21.1	6.6
7.0	1.1		6.4	660	23.9	6.2
9.0	1.1		5.6	616	7.9	5.5
15.0	1.1		4.7	540	7.7	4.8
0.059	1.2		28.2	1214	53.8	28.6
0.30	1.2		17.9	1505	82.3	18.1
0.40	1.2		14.3	1361	65.4	15.2
1.0	1.2		13.7	1561	105.5	12.3
3.0	1.2		7.6	1030	50.6	7.6
5.0						
7.0						
9.0	1.2		5.8	843	47.1	6.0
15.0	1.2		5.0	662	38.3	4.6
0.059	1.3		27.3	1516	69.2	28.4
1.0						
3.0						

NOTE: Soil colu

At bulk density of 1.1 gm./cm.^{3}, the force exerted by the seedling was maximum (65.1 gm.) at one bar tension and then decreased with increasing moisture tension. The least force (7.7 gm.) exerted was at fifteen bars tension. The magnitude of the force decreased rapidly from one bar tension to three bars tension, and continued to decrease between nine to fifteen bars tension, but at a slower rate. This was associated with a small change in moisture per cent between five and fifteen bars tension. The force exerted was maximum at one bar tension due to the combined effect of cohesive and adhesive forces of water molecules. This contributed to the resistance experienced by the seedlings.

With bulk density kept constant at 1.1 gm./cm.^{3}, the soil afforded less resistance to the seedling emergence as the moisture content decreased from one bar to higher bar tensions. This was due to the reduced cohesive forces of water molecules that tended to hold the soil particles together. Thus at higher soil moisture tension, the bulk density might be the major resistance encountered by the seedling as the Sequatchie sandy loam became more powdery and crumbled, thus affording least resistance for seedling emergence.

The relation between soil moisture per cent, time and the force at 1.1 gm./cm.^{3} bulk density is shown in Figures 5 and 6. There was a decrease in the time required for

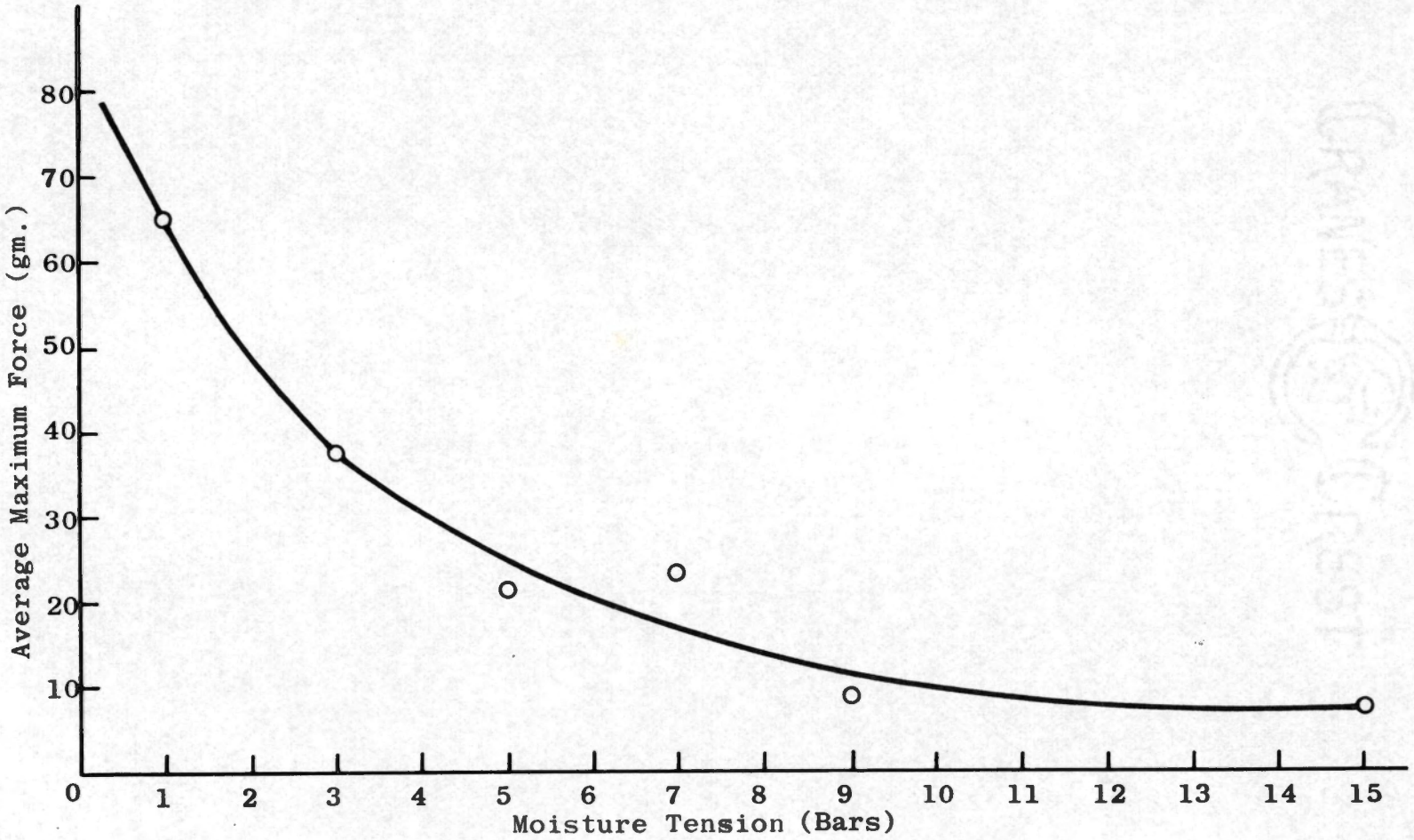


Figure 5. Force exerted by seedling at different moisture tensions of Sequatchie sandy loam at bulk density of 1.1 gm./cm.^{3}.

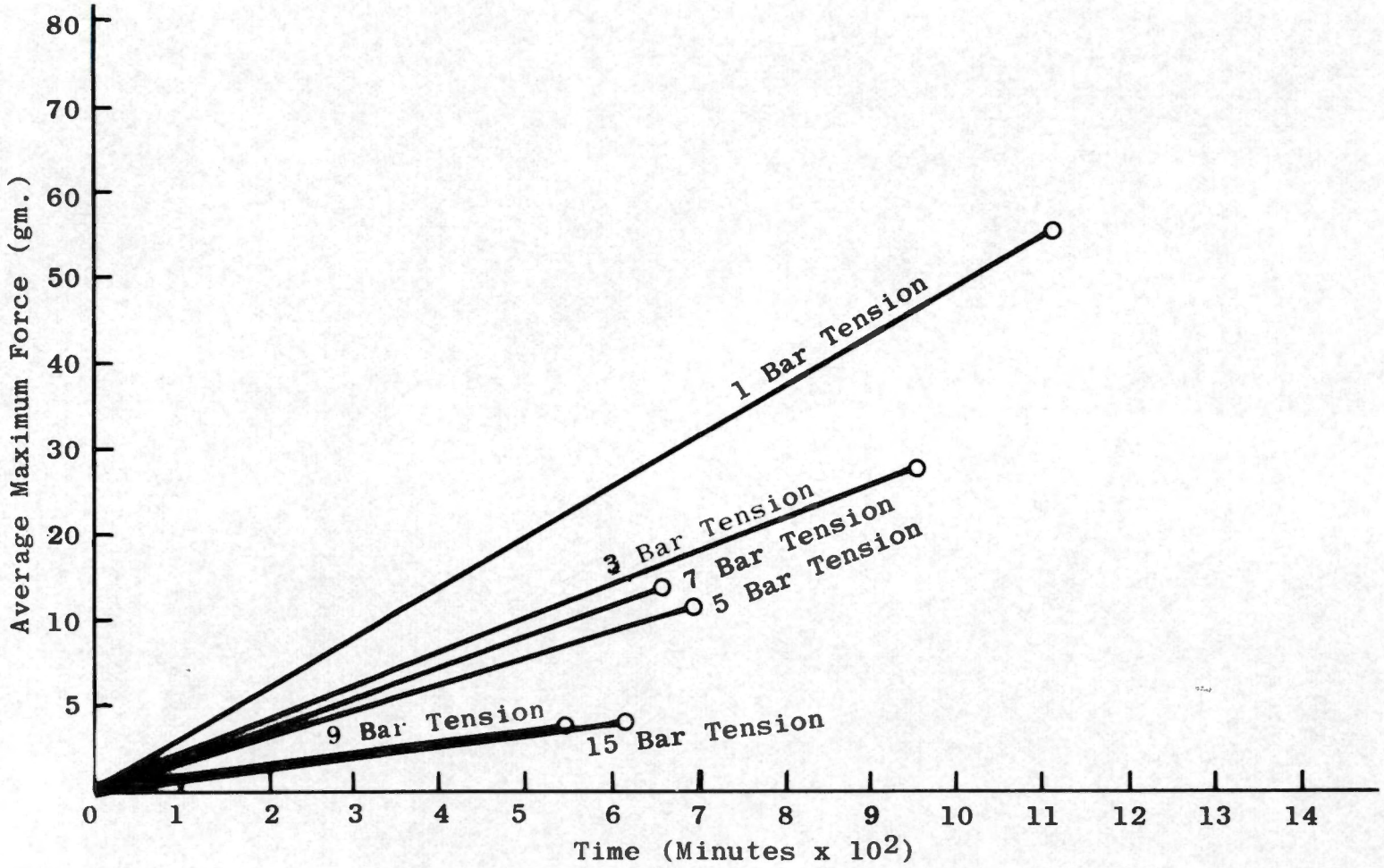


Figure 6. Relationship between time and force exerted by seedling at different moisture tensions at bulk density of 1.1 gm./cm.^{3}.

emergence (Figure 6) with an increase in the moisture tension or a decrease in the force required for emergence.

At bulk density of 1.2 gm./cm.^{3}, the force exerted by the seedling was lowest at 0.059 bar tension and increased at 0.30 and 0.40 bar tension. The force reached a maximum (105.5 gm.) at one bar tension and then decreased at higher tensions (Figure 7).

At lower moisture tensions, the cohesive force which decreases with the thickness of water films between the particles may be the principal factor rather than the adhesive force (Baver, 7). Thus with increasing moisture tension, the resistance experienced by the seedling reached a maximum at one bar tension due to both cohesive and adhesive forces. The cohesive forces then decreased with decreasing soil moisture; and for this soil reached a minimum at fifteen bars tension when the total of the adhesive and cohesive forces reached a second minimum. Therefore, the soil offered least resistance (the force required for emergence was 38.3 gm.) at fifteen bars tension; the resistance experienced by the seedling was probably proportional to the extent of the packing of the soil particles.

Figure 8 shows that the time required was higher with an increase in the force required for emergence. At a given soil-moisture content, the time required was more with increasing bulk density. or the time increased with an

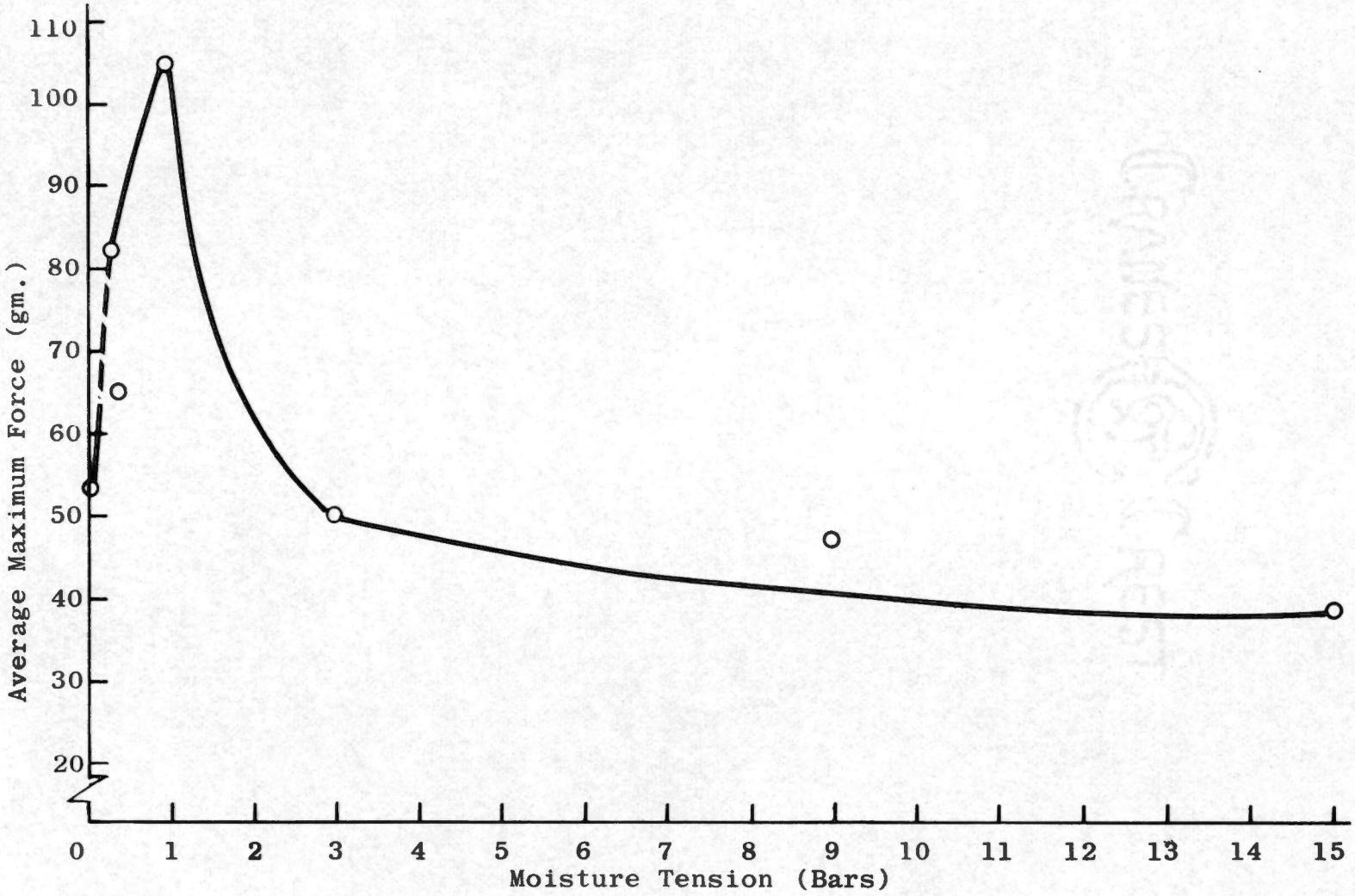


Figure 7. Force exerted by seedling at different moisture tensions of Sequatchie sandy loam at bulk density of 1.2 gm./cm.^{3}.

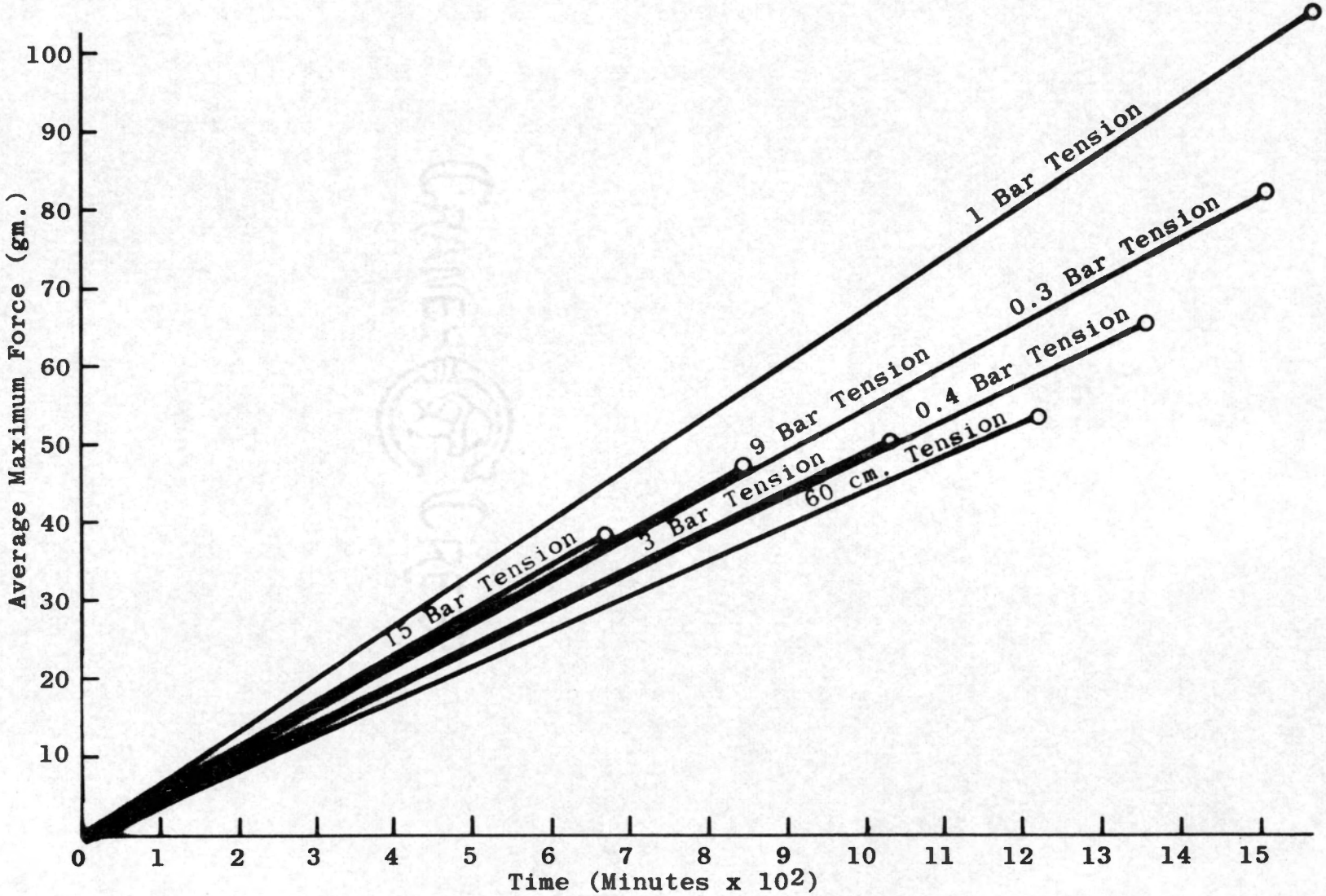


Figure 8. Relationship between time and force exerted by seedling at different moisture tensions at bulk density of 1.2 gm./$cm.^3$.

increase in the soil moisture content at a given bulk density up to one bar moisture tension. With increasing bulk density, there was an increase in the time and force required for emergence. The soil was more compact with increasing bulk density, and this factor also contributed to the resistance experienced by the seedling for emergence in a given space of soil. This effect was greater above one bar tension than at lower soil moisture tensions. Thus at higher soil moisture tensions, for Sequatchie sandy loam soil, the bulk density was a contributing factor to the resistance experienced by the seedling. These results are in agreement with Morton (44) who found that the energy required for emergence of a seedling increased directly with soil compactness and soil moisture content.

It was not possible to prepare a sample of 1.1 gm./ $cm.^3$ bulk density at 0.059 bar tension, because this soil settled down to a column length less than 20 mm. Water was squeezed out of the system when bulk density higher than 1.3 $gm./cm.^3$ was attempted, but this would be effected as increasing density reduces the per cent moisture at the lower tensions. At higher soil moisture tension, the soil could be prepared by compaction to a bulk density of 1.2 or 1.3 $gm./cm.^3$, but there was no emergence in certain treatments. The seedling exerted a force exceeding even 100 gm.; but as it experienced too great a resistance, it bent and

grew to the side of the box, and then the force exerted was released. Therefore, the complete data for higher bulk densities for some of the moisture treatments are not available. For higher bulk densities beyond 1.2 gm./cm.^{3} there was no emergence for soil moisture tensions beyond 0.059 bar tension. No emergence was also found for treatments of five and seven bars tension at bulk density of 1.2 gm./cm.^{3}.

Energies Involved in Seedling Emergence

The relationship between the force exerted by the seedling and the time was found to be essentially linear, as shown in Figures 9 and 10, for some of the treatments. Figure 9 shows the relationships between the force and time for different bulk densities of 1.1, 1.2 and 1.3 gm./cm.^{3}, and for 1 bar and 0.059 bar tensions. Figure 10 shows the plot of force and time for bulk densities 1.1 and 1.2 gm./cm.^{3} at the same tension of 15 bars. The relationships, as can be seen, were essentially linear. Figure 11 shows the relationship between the growth of the seedling and time. Two samples of soil with moisture percentages of 18.8 and 20.4 were used. The relationships were essentially linear.

Since both the above relationships were approximately linear, the energy E exerted by the seedling was calculated as follows:

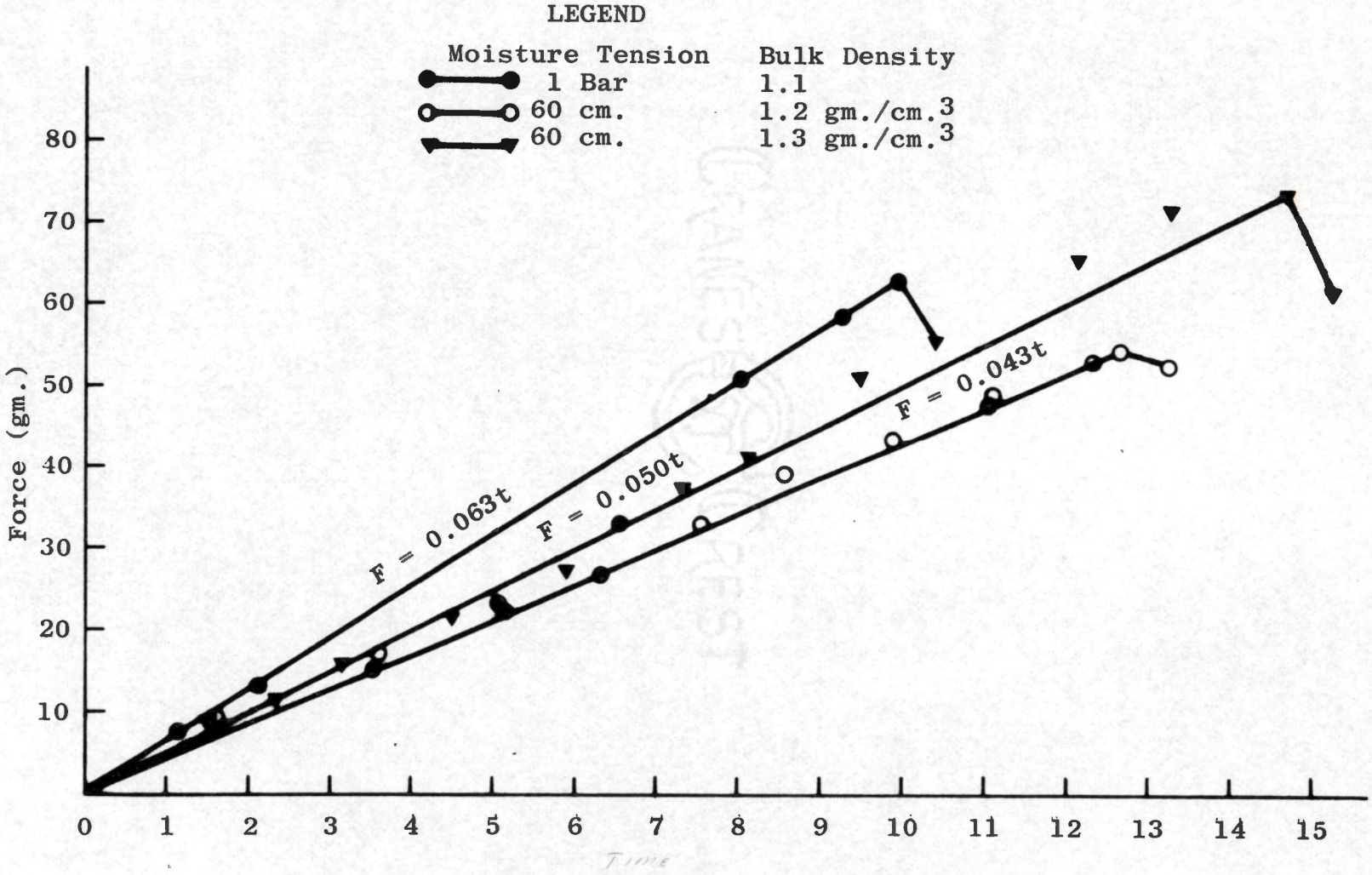


Figure 9. Relationship between force exerted by the seedling and time at bulk densities of 1.1, 1.2 and 1.3 gm./cm.^{3}.

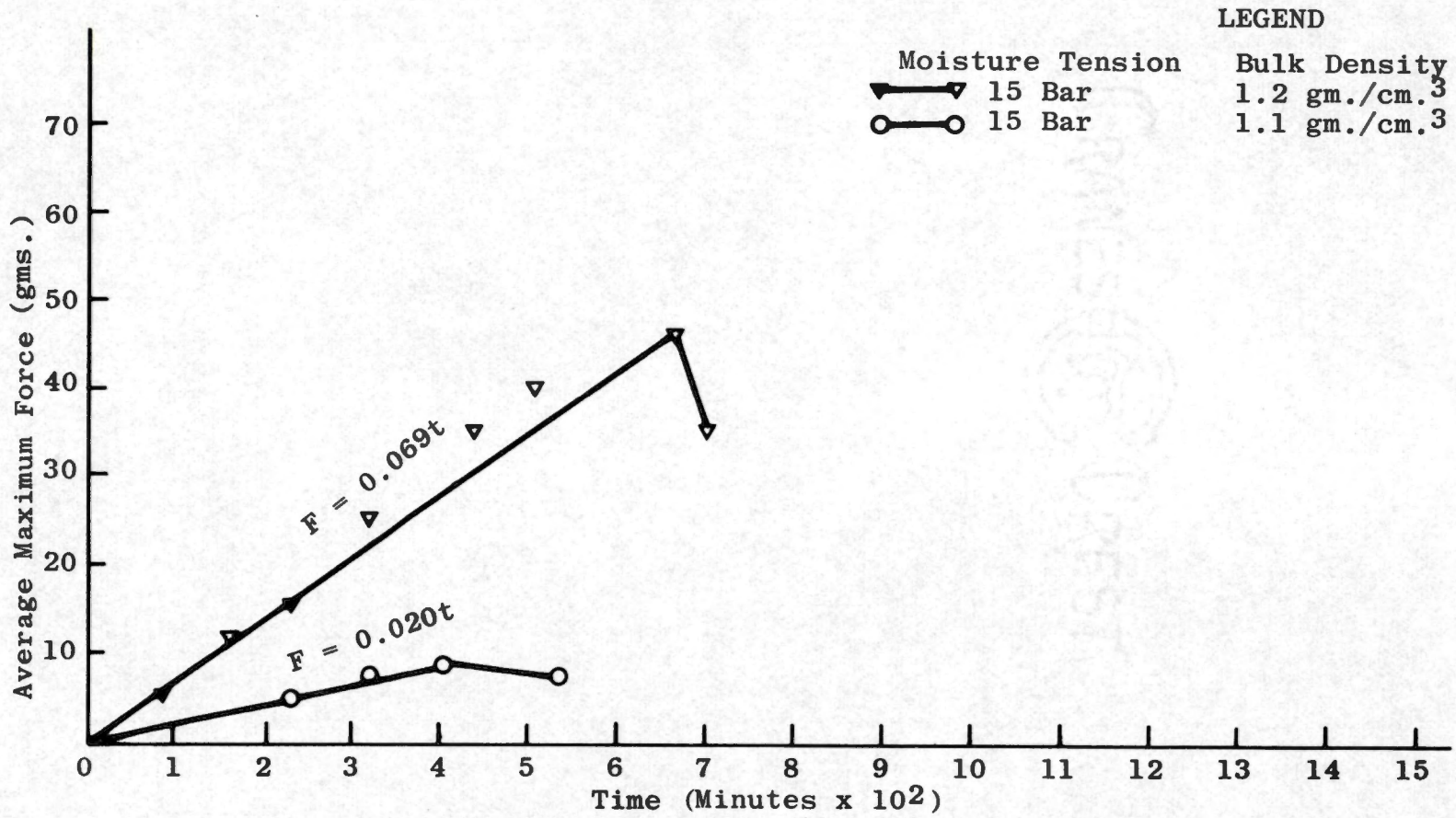


Figure 10. Relationship between force exerted by seedling with time at bulk densities of 1.1 and 1.2 gm./cm.^{3}.

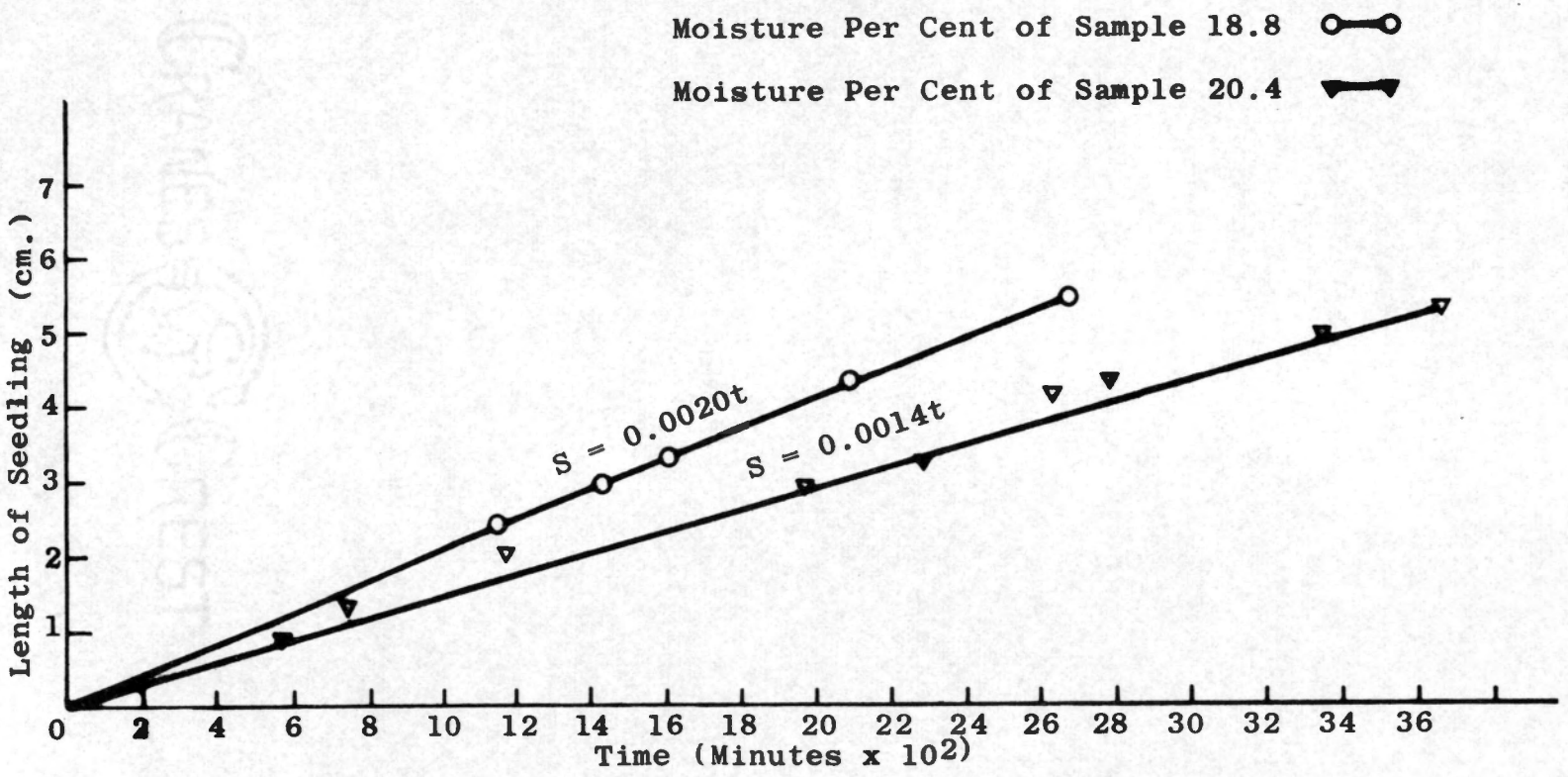


Figure 11. Relationship between seedling length and time.

$$E = \int_0^t F \, dS$$

where F = force exerted by the seedling, and

dS = change in the distance of the seedling with time t.

Since $F = a + b_1 t$

where a = 0 with the boundary condition that

F = 0 at time t = 0,

therefore $F = b_1 t$.

Again $S = a + b_2 t$

when S = the height of the seedling, and

a = 0 with the boundary condition that

S = 0 at time t = 0.

Therefore $dS = b_2 dt$.

Hence $$E = \int_0^t b_1 b_2 t \, dt$$
$$= b_1 b_2 t^2/2.$$

Taking $b_1 = F/t$ and $b_2 = S/t$

$$E = \frac{F \; S \; t^2}{t \; t \; 2}.$$

Keeping the dimensions of the cgs. system; and since

S = 2 cm.,

E = F gm.cm.

E = F 981 dyne cm. or F 981 ergs.

The relationships thus developed showed that the energy exerted by the seedling at a given soil moisture, bulk density and soil column, was independent of time.

The calculated energies exerted by the seedling at different moisture tensions and bulk densities are presented in Table 4 and Figure 12.

As the energies were proportional to the forces exerted by the seedling, the energies required for emergence followed the similar trends as that of the forces involved. At a bulk density of 1.1 gm./cm.^{3}, there was a decrease in the energy with increasing moisture tension from one bar tension and the maximum energy (0.00638 joules) was required at one bar tension. The energies were least at fifteen bars tension (0.00075 joules). At a bulk density of 1.2 gm./cm.^{3} the energies followed a similar trend as the forces for the emergence of the seedling. There was an increase in the energy with increased moisture tension from 0.059 bar to 0.30 bar tension but the energy decreased again up to 0.40 bar tension. The maximum energy exerted was 0.01047 joules at one bar tension, and again decreased with increasing soil

Table 4. Energies exerted by seedling at different soil moisture tensions and bulk densities for Sequatchie sandy loam

Moisture tension in bars	Average moisture per cent by weight	Bulk density gm./cm.^{3}	(Energies in joules x 10^{-3}) Replication I	Replication II	Replication III	Average
1.0	12.3	1.1	6.78	6.14	6.24	6.38
3.0	7.8	1.1	3.75	3.53	3.84	3.71
5.0	6.6	1.1	2.17	1.76	2.28	2.07
7.0	6.2	1.1	2,73	2.24	2.08	2.35
9.0	5.5	1.1	0.59	0.76	0.97	0.77
15.0	4.8	1.1	0.57	0.87	0.81	0.75
0.059	28.6	1.2	5.61	4.91	5.30	5.27
0.30	18.1	1.2	7.98	8.00	8.24	8.07
0.40	15.2	1.2	6.64	6.96	5.66	6.42
1.0	12.3	1.2	10.99	10.83	9.22	10.47
3.0	7.6	1.2	4.33	5.76	4.81	4.97
5.0		1.2	No emergence			
7.0		1.2	No emergence			
9.0	6.0	1.2	5.87	5.53	2.45	4.62
15.0	4.6	1.2	4.48	3.77	3.03	3.76
0.059	28.4	1.3	7.02	6.10	7.23	6.78
1.0		1.3	No emergence			
3.0		1.3	No emergence			

NOTE: Soil column 20 mm.

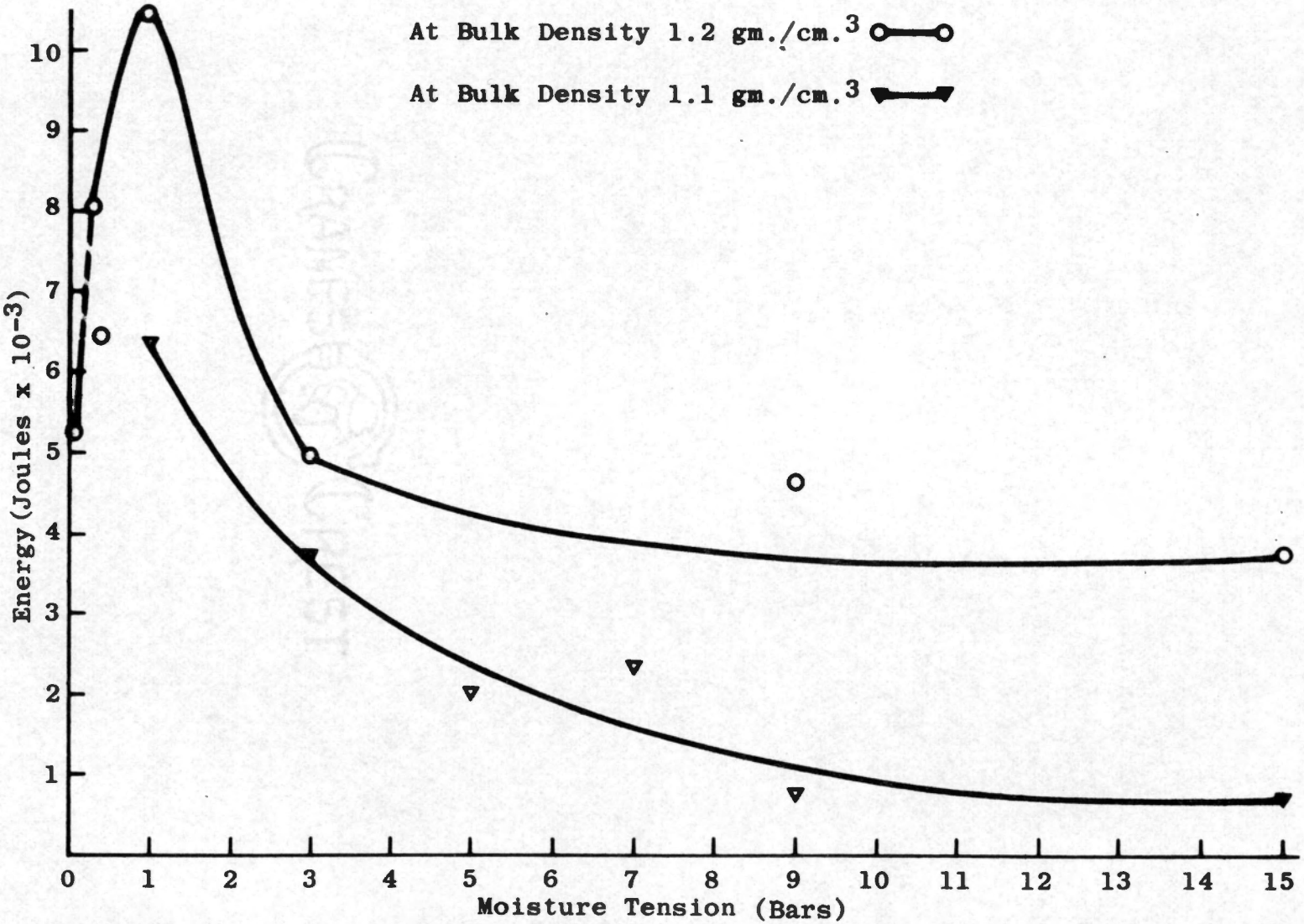


Figure 12. Energy exerted by seedling at different moisture tensions and bulk densities for Sequatchie sandy loam.

moisture tension (Figure 12). At a given soil moisture tension, there was an increase in the energy with increasing bulk density. This was more pronounced at higher moisture tensions, than at lower soil moisture tensions.

Computations of Pressures Involved in Seedling Emergence

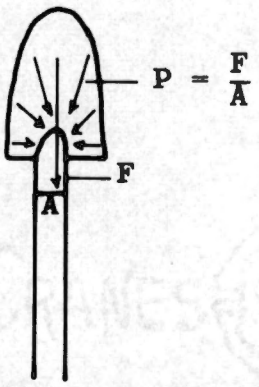
From the measured forces (F) and cross sectional areas (A) of the shoot, an average pressure distribution (P) over the tip surface of the seedling could be computed according to Figure 13 as

$$P = F/A.$$

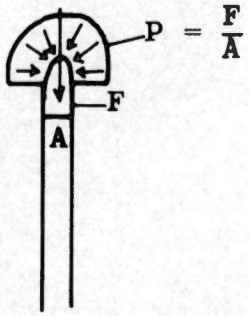
If the maximum measured force ($F_{max.}$) was substituted, the resulting pressure would be the maximum average pressure ($P_{max.}$) equivalent to that force ($F_{max.}$) experienced by the seedling. Since the cross section of the seedling was very nearly constant except at the tip, it was assumed that the pressure variations over that small area of the tip were insignificant (Figure 13, a). In that case the computed $P_{max.}$ would be approximately equal to that maximum pressure actually experienced by the seedling. If the pressure over the tip surface were actually constant (Figure 13, b), the computed pressure would be exact as

$$P = F/A = F/\pi r^2$$
$$= F/0.0134 \text{ gm./cm.}^2$$

since r = 0.1 cm. the average radius of the seedlings. The



(a) Actual Seedling



(b) Mathematical Model

Figure 13. Pressure distribution over the tip of the seedling.

pressures exerted by the seedling at different bulk densities, and moisture tensions are given in Table 5 and Figure 14.

Since the pressure exerted was proportional to the diameter of the seedling which was assumed to be constant, the pressures involved also followed the same trend as the force and energies required for emergence. The pressure required was maximum (2072.2 gm./cm.^{2} or 29.42 lb./in.^{2}) at one bar tension at bulk density of 1.1 gm./cm.^{3}, while it was least (244.1 gm./cm.^{2} or 3.47 lb./in.^{2}) at fifteen bars tension. There was a rapid decrease of pressure from one bar to five bars with a less gradual decrease up to fifteen bars tension. This result, as pointed out earlier, might be associated with the small change in the moisture per cent from five to fifteen bars tension.

At a bulk density of 1.2 gm./cm.^{3}, the pressure required at 0.059 bar tension was 1712.3 gm./cm.^{2} or 24.31 lb./in.^{2}. It increased up to a moisture tension of 0.30, and then it decreased with increasing moisture tension. The maximum (3358.7 gm.cm.^{2} or 47.69 lb./in.^{2}) was attained at one bar, and then the pressure decreased with increasing soil moisture tension. It was minimum (1220.8 gm./cm.^{2} or 17.34 lb./in.^{2}) at fifteen bars tension (Figure 14).

The pressure required for emergence increased with an increase in bulk density. This was more pronounced at

Table 5. Pressures exerted by seedling for emergence at different moisture tensions and bulk densities of Sequatchie sandy loam

Moisture tension in bars	Average moisture per cent by weight	Bulk density gm./cm.^{3}	(Pressure in gm./cm.^{2}) Replication I	Replication II	Replication III	Average
1.0	12.3	1.1	2200.6	1990.4	2025.5	2072.2
3.0	7.8	1.1	1216.6	1146.5	1243.2	1202.6
5.0	6.6	1.1	703.8	573.2	738.8	671.9
7.0	6.2	1.1	885.4	726.1	675.2	762.2
9.0	5.5	1.1	191.1	248.4	315.3	251.6
15.0	4.8	1.1	184.7	283.4	264.3	244.1
0.059	28.6	1.2	1821.6	1595.5	1719.7	1712.3
0.30	18.1	1.2	2589.2	2595.5	2675.2	2620.0
0.40	15.2	1.2	2156.0	2258.0	1837.6	2083.8
1.0	12.3	1.2	3566.9	3515.9	2993.6	3358.7
3.0	7.6	1.2	1404.4	1869.4	1560.5	1611.4
5.0		1.2	No emergence			
7.0		1.2	No emergence			
9.0	6.0	1.2	1904.4	1796.2	796.2	1498.9
15.0	4.6	1.2	1455.4	1222.9	984.1	1220.8
0.059	28.4	1.3	2280.2	1980.9	2347.1	2202.7
1.0		1.3	No emergence			
3.0		1.3	No emergence			

NOTE: Soil column 20 mm.

gm./cm.^{2} x 0.0142 = lb./in.^{2}

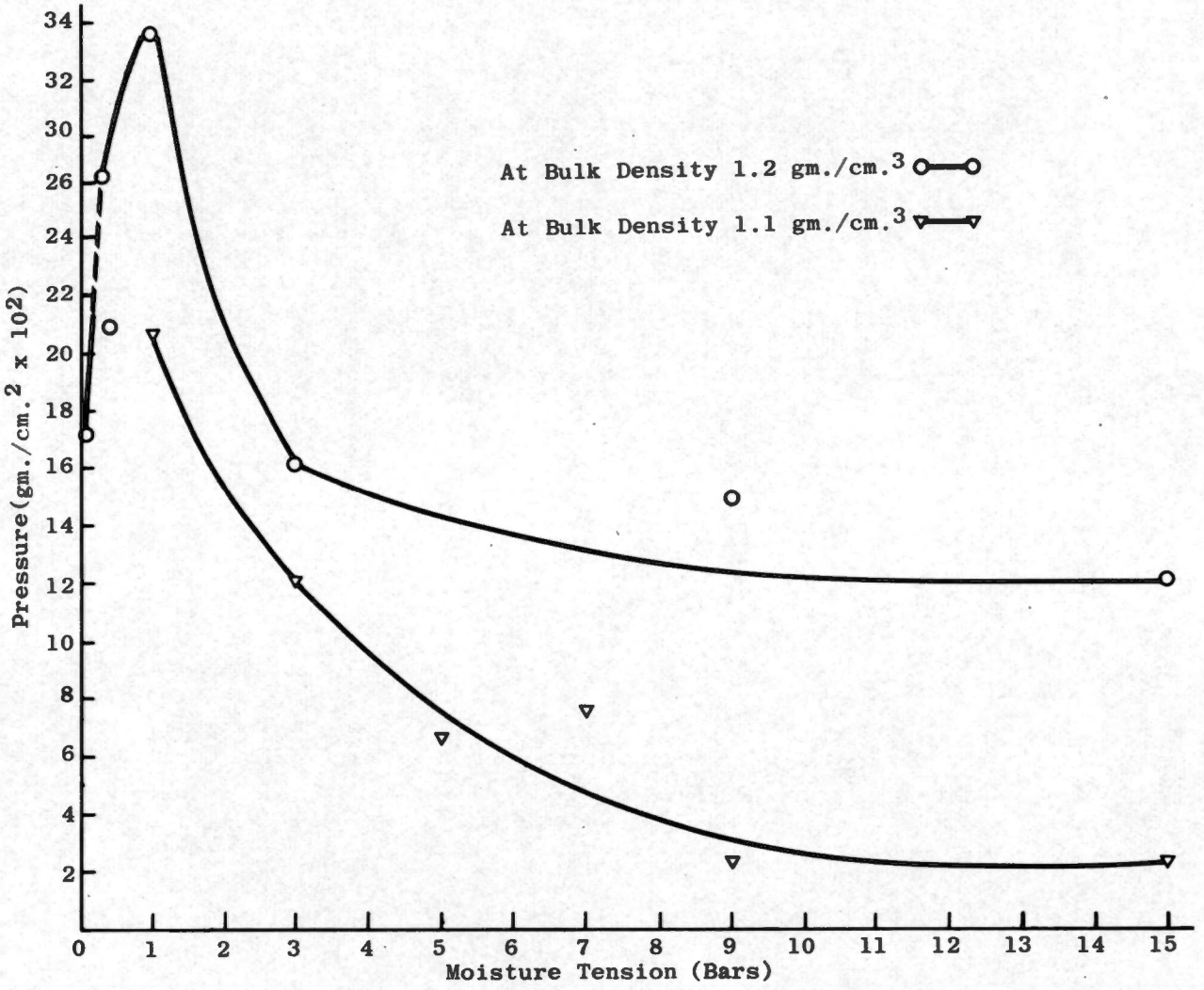


Figure 14. Pressure exerted by seedling at different moisture tensions and bulk densities for Sequatchie sandy loam.

higher soil moisture tensions than at lower soil moisture tensions. For example, at 0.059 bar tension, the pressure required for emergence was 1712.3 gm./cm.^{2} or 24.31 lb./in.^{2} at 1.2 gm./cm.^{3} bulk density while it was 2202.7 gm./cm.^{2} or 31.27 lb./in.^{2} at a bulk density 1.3 gm./cm.^{3}.

The forces involved do not reflect the actual field conditions. The moisture differential between the shoot and root zone would be small under normal conditions. The shoot may not be able to penetrate the soil and emerge unless enough moisture is present for the root growth. Consequently, the emergence of a seedling through the soil may be restricted to considerably lower moisture tensions of the soil which is conducive to seedling growth.

Although the ionic effect was not included in this study, it may be expected that the salt concentration would contribute to the total soil moisture tension through the osmotic effect. However, it has been shown that under normal soil conditions, the osmotic gradients become effective as the matric potential reaches about one bar tension (28). Therefore the seedling emergence may be influenced by the osmotic effect, but probably beyond one bar tension.

In clay type soils, the cohesion forces would be more effective at higher soil moisture tensions. Hence the forces required for emergence may be expected to be more at comparatively higher tensions, as contrasted to the sandy

type soils. Again little or no emergence would be expected at still higher soil moisture tensions due to higher magnitude of cohesive forces between the soil particles.

CHAPTER V

SUMMARY AND CONCLUSIONS

Energies involved in the emergence of a seedling through a soil column as influenced by different moisture tensions and bulk densities were studied. Sequatchie sandy loam was used for the experiment. Each soil column of 20 mm. depth was prepared at a predetermined moisture tension and bulk density using either the tension table, porous plate or the pressure membrane apparatus. The seedling was mounted in a small plastic cap and was placed on a Sartorius balance pan. The dial of the balance was outside the wooden box, while the pan and the seedling were set up in the wooden box which was light tight. The soil column in an aluminum box was mounted on a clamp stand and placed just over the seedling. The change in the dial reading (the force exerted) with time was photographed by a movie camera using the time-lapse technique.

The force required for seedling emergence decreased with increase in soil moisture tension from 1 to 15 bars at bulk density of 1.1 gm./cm.^{3}. At the bulk density of 1.2 gm./cm.^{3}, the force was less at 0.059 bar tension and increased up to one bar tension when it was maximum, and it decreased with a further increase in soil moisture tension.

At lower soil moisture tensions, the cohesive force of water which decreases with the thickness of water films between the particles, was the principal factor rather than the adhesive force. The resistance experienced by the seedling reached a maximum at one bar tension due to both cohesive and adhesive forces as the moisture tension increased from 0.059 bar to one bar tension. The total cohesive and adhesive forces reached a minimum at fifteen bars tension. The soil offered least resistance at fifteen bars tension for the seedling emergence, and the resistance experienced by the seedling was due to the extent of the packing of the soil particles.

At a given moisture tension, the forces exerted were greater at higher bulk densities, the increase being more pronounced at higher moisture tensions than at lower moisture tensions. The relationship between the rate of force exerted and the time was approximately linear. The time and the distance of penetration of the seedling were also found to be linearly related. Under the experimental conditions with Sequatchie sandy loam, the forces exerted were found to be independent of the time required for emergence at a given bulk density and soil moisture. The energies required were also found to be proportional to the forces required for seedling emergence. The pressure experienced by the seedling during its emergence was found to follow the

similar trends to the force and energy, assuming that the seedling had a uniform diameter of 0.2 cm. The results indicate the general trends.

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LITERATURE CITED

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*Original not seen.