3

77

BARD

FINAL REPORT

PROJECT NO. US-2794-96

**Characterization of Post-Tillage Soil Fragmentation
and Rejoining Affecting Soil Pore Space Evolution
and Transport Properties**

V.A. Snyder, D. Or, A. Hadas, S. Assouline

2002

10
2557

BARD Final Scientific Report
Cover Page

Date of Submission of the report:

BARD Project Number: US-2794-96

Project Title: Characterization of Post-Tillage Soil Fragmentation and Rejoining Affecting Soil Pore Space Evolution & Transport Properties.

Investigators

Institutions

Principal Investigator (PI):

Victor A. Snyder

University of Puerto Rico (USA)

Co-Principal Investigator (Co-PI):

Dani Or

Utah State University (USA)

Amos Hadas

ARO, The Volcani Center (ISRAEL)

Collaborating Investigators:

Shmuel Assouline

ARO, The Volcani Center (ISRAEL)

Keywords *not* appearing in the title and in order of importance. Avoid abbreviations.
Soil rheology, soil shear strength, soil viscosity, soil compaction,
soil consolidation, fracture mechanics, elastoplastic fracture,
Fokker-Planck equation, soil structure
Abbreviations commonly used in the report, in alphabetical order:

FPE - Fokker Planck Equation

Budget: IS: \$ 91,200

US: \$ 198,900

Total: \$ 290,100

Signature
Principal Investigator

Signature
Authorizing Official, Principal Institution

BARD Final Scientific Report Cover Page

Publication Summary (numbers)

	Joint IS/US authorship	US Authors only	Israeli Authors only	Total
Refereed (published, in press, accepted)		6		6
Submitted, in review, in preparation		8	4	12
Invited review papers				
Book chapters				
Books				
Master theses				
Ph.D. theses		1		1
Abstracts		16		16
Not refereed (proceedings, reports, etc.)		1		1

Postdoctoral Training: List the names and social security/identity numbers of all postdocs who received more than 50% of their funding by the grant.

Cooperation Summary (numbers)

	From US to Israel	From Israel to US	Together, elsewhere	Total
Short Visits & Meetings	1	1	2	4
Longer Visits (Sabbaticals)				

Description of Cooperation:

In addition to communicating by phone and internet, Project Investigators participated in a number of scientific meetings in the U.S., Israel, France and Germany where they met to discuss the Project. Soil materials and data from Puerto Rico were used in the Research program in Utah.

Patent Summary (numbers)

	Israeli inventor (s) only	US inventor (s) only	Joint IS/US inventors	Total
Submitted				
Issued (allowed)				
Licensed				

Abstract

Tillage modifies soil structure, altering conditions for plant growth and transport processes through the soil. However, the resulting loose structure is unstable and susceptible to collapse due to aggregate fragmentation during wetting and drying cycles, and coalescence of moist aggregates by internal capillary forces and external compactive stresses. Presently, limited understanding of these complex processes often leads to consideration of the soil plow layer as a static porous medium. With the purpose of filling some of this knowledge gap, the objectives of this Project were to: 1) Identify and quantify the major factors causing breakdown of primary soil fragments produced by tillage into smaller secondary fragments; 2) Identify and quantify the physical processes involved in the coalescence of primary and secondary fragments and surfaces of weakness; 3) Measure temporal changes in pore-size distributions and hydraulic properties of reconstructed aggregate beds as a function of specified initial conditions and wetting/drying events; and 4) Construct a process-based model of post-tillage changes in soil structural and hydraulic properties of the plow layer and validate it against field experiments. A dynamic theory of capillary-driven plastic deformation of adjoining aggregates was developed, where instantaneous rate of change in geometry of aggregates and inter-aggregate pores was related to current geometry of the solid-gas-liquid system and measured soil rheological functions. The theory and supporting data showed that consolidation of aggregate beds is largely an event-driven process, restricted to a fairly narrow range of soil water contents where capillary suction is great enough to generate coalescence but where soil mechanical strength is still low enough to allow plastic deformation of aggregates. The theory was also used to explain effects of transient external loading on compaction of aggregate beds. A stochastic formalism was developed for modeling soil pore space evolution, based on the Fokker Planck equation (FPE). Analytical solutions for the FPE were developed, with parameters which can be measured empirically or related to the mechanistic aggregate deformation model. Pre-existing results from field experiments were used to illustrate how the FPE formalism can be applied to field data. Fragmentation of soil clods after tillage was observed to be an event-driven (as opposed to continuous) process that occurred only during wetting, and only as clods approached the saturation point. The major mechanism of fragmentation of large aggregates seemed to be differential soil swelling behind the wetting front. Aggregate "explosion" due to air entrapment seemed limited to small aggregates wetted simultaneously over their entire surface. Breakdown of large aggregates from 11 clay soils during successive wetting and drying cycles produced fragment size distributions which differed primarily by a scale factor λ (essentially equivalent to the Van Bavel mean weight diameter), so that evolution of fragment size distributions could be modeled in terms of changes in λ . For a given number of wetting and drying cycles, λ decreased systematically with increasing plasticity index. When air-dry soil clods were slightly weakened by a single wetting event, and then allowed to "age" for six weeks at constant high water content, drop-shatter resistance in aged relative to non-aged clods was found to increase in proportion to plasticity index. This seemed consistent with the rheological model, which predicts faster plastic coalescence around small voids and sharp cracks (with resulting soil strengthening) in soils with low resistance to plastic yield and flow. A new theory of crack growth in "idealized" elastoplastic materials was formulated, with potential application to soil fracture phenomena. The theory was preliminarily (and successfully) tested using carbon steel, a ductile material which closely approximates ideal elastoplastic behavior, and for which the necessary fracture data existed in the literature.

Achievements

Main scientific achievements or innovations, and their significance:

1. A quantitative, physically based model was developed for predicting time-dependent plastic deformation of aggregate beds and inter-aggregate pore space under transient soil moisture regimes and external loading, and effects on hydraulic properties. Input requirements are: 1) the initial size distribution and spatial arrangement of aggregates; 2) experimentally measurable Bingham rheological parameters as a function of soil water content; 3) statistical hydraulic conductivity and water retention functions; and 4) history of external loading and hydraulic conditions imposed at the soil boundaries. At least in a qualitative sense, the theory successfully predicts observed macroscopic phenomena, such as soil volume change under cyclic loading and wetting and drying, that previously could only be modeled empirically. It is generally difficult to quantify initial structure of aggregate beds and statistics of load transmission between aggregates, but the theory can still be used to examine well-defined limiting cases which bracket “typical” soil conditions. The theory also provides new insight into macroscopic variables and their functions which should be measured in characterizing soil mechanical behavior at the macroscopic scale. An important implication for irrigation and drainage management is that, in absence of external loads, soil settlement following tillage is restricted to a narrow “window of opportunity” where water content is high enough to cause low yield stress and high viscosity of the solid matrix, yet low enough to cause capillary suctions capable of driving the deformation process.
2. A stochastic formalism based on the Fokker Planck differential equation (FPE) was developed for describing temporal evolution of mean and variance of pore-size distributions and loss of pore space in soils. Parameters of the FPE are determined empirically from macroscopic moisture retention data, or derived from the physically based model described in (1) above. Analytical solution of the FPE was achieved for certain special cases.
3. Fragmentation of large aggregates from 11 clay soils of variable mineralogy during successive wetting and drying cycles was found to obey a simple scaling rule. Aggregate populations for a given soil and number of wetting and drying cycles differed from the populations for other soils and numbers of wetting and drying cycles only by a scale factor λ , proportional to the Van Bavel mean weight diameter. Such scaling behavior, which requires no a-priori assumption on the type of distribution (log-normal, Weibul, etc), allows modeling

evolution of fragment size distributions as evolution of λ . The evolution of λ as a function of number of wetting and drying cycles obeyed a simple power law, the parameters of which varied systematically with soil shrink-swell behavior as quantified by the plasticity index. Fragmentation was primarily a wetting-induced process, apparently caused by differential soil swelling behind the wetting front. The classic explanation of air entrapment and “explosion” of aggregates seemed applicable only in the case of small aggregates where wetting occurs simultaneously around the entire periphery of the aggregate. As in (1) above, the event-driven nature of aggregate fragmentation has important implications for post-tillage soil structure modification through irrigation management. It is also consistent with observations in that fracture properties of soil aggregates sampled in the field correlated very little with “static” properties such as texture and content of organic matter and CaCO_3 .

4. The ability of fracture-weakened aggregates to strengthen over time (a process known as “aging”) at constant high water content, varied directly with soil plasticity index. This seemed consistent with the theory in (1) above, which predicts that plastic flow of solid material into voids with high surface curvature, such as small pores and sharp crack tips, will occur faster in soils with low resistance to plastic yield and flow (high plasticity index ?).
5. A new quasistatic mechanical theory of fracture was developed for idealized elastoplastic materials, and partially tested against available fracture data for carbon steel, a ductile material which closely approximates idealized elastoplastic behavior. By incorporating irreversible plastic deformation into its formal structure, the theory represents a major improvement over current elastoplastic fracture theory based on the Rice-Cherapnov J-integral, which treats irreversible elastoplastic deformation as reversible non-linear elastic behavior. Although the theory has not yet been tested in soil materials, it is expected to ultimately provide an improved theoretical framework for characterizing fracture phenomena in soils.

Potential for application and estimated time scale (immediate, medium or long term)

Results described in (1), (3) and (4) above point to major opportunities for manipulating post-tillage soil structure through irrigation and drainage management, particularly in arid or semi-arid regions where precipitation is a manageable factor. These will need to be carefully weighed against irrigation and drainage demands of crops. In addition to their academic value, the

theories described in (1), (2) and (3) above provide new insight into variables and processes which should be considered in characterizing soil deformation and fracture phenomena. This should have a relatively short term impact (0-5 years after publishing) on stimulating field experiments for obtaining soil-specific parameters and corroborating major predictions at the field scale. Applications at the farm scale are most likely over a medium time scale (5-10 years).

Estimated economic benefits .unrealistic to predict at this stage.

Estimated impact, in % change .unrealistic to predict at this stage.

Other (spin off) benefits .Due to their general nature, the theories described in (1), (2) and (4) should be of interest to extra-agricultural disciplines, particularly ceramic engineering and fracture mechanics.

Details of Cooperation .In addition to communicating by telephone and internet, BARD Project investigators participated in a number of scientific meetings in the U.S., Germany, France and Israel. This provided ample opportunity to discuss issues related to the Project. Research data and soil materials from Puerto Rico were used by the Utah (USA) group as input into theoretical work described in (1) and (2).

List of Refereed Publications

Ghezzehei, T.A. and D. Or, (2000). Dynamics of soil aggregate coalescence governed by capillary and tillage processes. *Water Resour. Res.* 36:367-379.

Or, D. and T.A. Ghezzehei, (2000). Dripping into subterranean cavities from unsaturated fractures under evaporative conditions. *Water Resour. Res.* 36:381-393.

Or, D., F.J. Leij, V.A. Snyder and T.A. Ghezzehei, (2000). Stochastic model for post-tillage soil pore space evolution. *Water Resour. Res.* 36:1641-1652.

Ghezzehei, T.A. and D. Or. (2001). Rheological properties of unsaturated soils and clays under steady and oscillatory stresses. *Soil Sci. Soc. Am. J.* 65:624-637.

Other articles in Proceedings, in Press, in Review, or in Preparation are reproduced in the Appendix.