2011

Use Of Vegetative Mulch As Daily And Intermediate Landfill Cover

Assal Edwar Haddad
University of Central Florida

USE OF VEGETATIVE MULCH AS DAILY AND INTERMEDIATE LANDFILL COVER

by

ASSAL EDWAR HADDAD
B.S. Jordan University of Science and Technology, 2001
MS ENV E. Jordan University of Science and Technology, 2004

A dissertation submitted in partial fulfillment of the requirements
for the degree of Doctor of Environmental Engineering
in the Department of Civil, Environmental, and Construction Engineering
in the College of Engineering and Computer Science
at the University of Central Florida
Orlando, Florida
Spring Term
2011

Major Professors:
Debra Reinhart
Manoj Chopra

ABSTRACT

Management of yard waste is a significant challenge in the US, where in 2008 13.2% of the 250 million tons of municipal solid waste (MSW) was reported to be yard waste. This study describes research conducted in the laboratory and field to examine the application of vegetative mulch as daily and intermediate landfill cover. Mulch was found to exhibit stronger physical properties than soil, leading to a more stable landfill slope. Compaction of mulch was found to be significantly greater than soil, potentially resulting in airspace recovery. Degradation of mulch produced a soil-like material; degradation resulted in lower physical strength and hydraulic conductivity and higher bulk density when compared with fresh mulch. Mulch covers in the field permitted higher infiltration rates at high rain intensities than soil covers, and also generated less runoff due to greater porosity and hydraulic conductivity as compared to soil. Mulch covers appear to promote methane oxidation more than soil covers, although it should be noted that methane input to mulch covers was more than an order of magnitude greater than to soil plots. Life cycle assessment (LCA) showed that, considering carbon sequestration, use of green waste as landfill cover saves GHG emissions and is a better environmental management option compared to composting and use of green waste as biofuel.

This dissertation is dedicated to my brother Sizeph Haddad

ACKNOWLEDGMENTS

I would like to thank my advisor, Dr Debra Reinhart, for guiding me through this research and for providing me the needed support with a generous and patient heart and mind. Also, I would like to thank my co-adviser, Dr. Manoj Chopra, for his help, time, and for his enthusiasm for this research. Without their motivation and dedication this research would have never been possible.

I would also like to thank my friends, Ikenna Uju, Ikiensinma Gogo-Abite, Jumoke Faborode, Stephanie Bolyard, Samar Younes, Washington Washbrum, Hamid Amini, and Ania Rusnak for their friendship and their support on and off campus.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1: INTRODUCTION

Background Information

Management of yard waste is a significant challenge in the US, where, in 2008, yard waste was reported to be 13.2% of the 250 million tons of municipal solid waste (MSW) (USEPA, 2008). According to Subtitle D of the Resource Conservation and Recovery Act (RCRA) codified in the Code of Federal Regulation (CFR) 258.21 Section (a); landfill owners and operators are required to cover the active face of the landfill with a minimum of 15 cm of earthen material at the end of every day (or at more frequent intervals if necessary) to control disease vectors, fires, odors, blowing litter, and scavenging. Florida regulations require an intermediate cover in addition to the 15-cm daily cover to be applied and maintained within seven days of cell completion if additional solid waste will not be deposited within 180 days of cell completion (62-701.500 Landfill Operation Requirements, Florida Department of Environmental Protection, FDEP). Many landfill operators must import cover soil from outside of the facility, increasing operating costs. Section CFR 258.21(b) allows the use of alternative cover materials if the landfill owner or operator demonstrates that the alternative material and thickness will function the same as a soil cover and does not present a threat to human health and the environment.

Materials for alternative landfill covers investigated to date include paper mill sludge, fly ash, mulched wood material, tarps, foams, and shredder fluff (Bracci et al., 1995; Bradley et al., 2001; Carson, 1992l; Hancock et al., 1999; Shimaoka et al., 1997). Haughey (2001) classified alternative daily covers into three broad categories; blankets, sprays, and waste materials. With the increasing drive towards sustainable waste management, use of waste-derived materials as ADC appears favorable. Further, it has an advantage over other forms of ADC because a tipping fee is collected for disposal. Although the waste-derived material ADC does consume landfill capacity, it is probably space that would be utilized anyway, therefore, the volume associated with cover soil is still avoided (Haughey 2001). It has been shown that compacted municipal solid waste (MSW) compost with low hydraulic conductivity as much as (2×10^{-10} m/s) can be used effectively as an alternative material to clay in landfill covers or liners because it has more resistance to the increase in hydraulic conductivity caused by desiccation and freeze-thaw and more shear strength than compacted clay (Benson and Othman 1993). Compost covers have the ability to reduce odorous emissions from landfill sites by up to 97% (Hurst et al. 2004). Compost covers were also found to be capable of methane oxidation (Humer & Lechner 1999). The ability of compost to remove chlorinated hydrocarbons and sulfur compounds has been reported by Muntoni and Cossu (1997).

Because of its volume and potential use as a soil amendment, the disposal of yard waste in lined landfills is banned in most states. Consequently, green waste is frequently composted, combusted, or mulched in preparation for recycling. Composting involves the aerobic biological degradation of yard waste to a soil-like material which is a beneficial additive to soils. It improves soil water-holding capacity, drainage and aeration, and it also increases the percentage of organic materials in soils. Mulching, on the other hand, involves size reduction and homogenizing without biological processing requiring less time, land, quality control, processing, and screening and thus, lower cost in comparison to compost production. Grass-rich green waste can cause odor issues at composting facilities if improperly stored. Therefore, municipalities are investigating alternative strategies to reduce green waste volumes during peak periods such as encouraging residents to leave clippings on the lawn and direct application of green waste to agricultural land (Uhlar-Heffner et al., 1998). In Florida, a number of waste management facilities (WMF) offer ground green waste (mulch) to the public to be used for agricultural and horticultural purposes. Most green waste is a beneficial soil amendment because it is a source of plant nutrients and organic matter. Allowing public access to mulch prior to composting also provides an outlet for handling high volumes of materials at compost facilities (Bary et al. 2005). Green waste without further processing has been used on a variety of crops in western Washington, including sweet corn, silage corn, rhubarb, flower bulbs, cabbage, and squash (Cogger et al. 2002). Storage of green waste for extended periods of time (more than a week) should be avoided to prevent odor generation (Cogger et al. 2002). Despite the low cost of managing green waste as mulch as opposed to composting, the quality of the fresh mulch as a soil conditioner/fertilizer is poor (Cogger et al. 2002); fresh mulch contains weed seeds and non-degradable material, and if not screened, excessive fractions of large particles. Also, from an energy consumption point of view, the numerous trips by private vehicles picking up mulch has a higher environmental impact than fewer trips carried out by large vehicles delivering compost to a commercial point of sale and use.

Research Objectives and Scope of Work

Since mulch is generated in the process of producing compost from yard waste, it is believed that the use of mulch as an ADC will be feasible since this will eliminate the costs of composting. However, mulch has never been evaluated for use as an ADC. This study is designed to evaluate the potential benefits and challenges of the use of vegetative mulch as daily and intermediate landfill cover. Use of mulch as cover material may provide a significant cost savings, could save space in landfills, and could result in carbon sequestration. There are two goals for this research:

1. Examine the application of vegetative mulch in daily and intermediate cover in landfill systems through laboratory and field testing,
2. Evaluate the carbon balance in landfills using mulch as a daily and intermediate cover, and

The specific objectives are to evaluate:

1. Potential for infiltration through mulch by testing the hydraulic conductivity of mulch in the laboratory,
2. The effect of mulch covers on geotechnical stability of slopes through laboratory testing of the shear strength of mulch samples,
3. The effect of seasonal changes on the quality of mulch and its function as daily and intermediate cover,
4. The effect of mulch covers on geotechnical stability of slopes through modeling,

5. Potential for infiltration through mulch by testing the hydraulic conductivity of mulch in the field,
6. Hydraulic behavior of mulch covers using field plots and water balance modeling using the Hydrologic Evaluation of Landfill Performance (HELP) model.
7. The resistance of mulch to erosion by monitoring the change in the thickness of the field plots mulch cover,
8. The role mulch covers play in controlling gas emissions,
9. The effect of aging on the physical and hydraulic properties of mulched yard waste used as landfill cover, and
10. Carbon emissions and carbon sequestration of yard waste mulching and use as landfill daily and intermediate cover in comparison to composting and incineration through Life Cycle Assessment (LCA).

Mulch samples have been collected from different parts of Florida over four seasons and their geotechnical and hydraulic properties have been evaluated. Data collected from the laboratory tests were used to develop models that assess the slope stability of MSW landfill with mulch as daily and intermediate cover. Field tests took place at a landfill in Florida where five plots were constructed over ten-year old waste to compare soil and mulch covers. Gas flux measurements were made over the plots every two weeks to observe the gas control each type of cover provides. Water balance measurements and calculations were carried out before and after storm events to compare the infiltration of precipitation through the cover materials and the generated runoff. HELP model was used to study the hydraulic behavior of daily and intermediate mulch covers and MSW under different climatic conditions based on data collected from laboratory and field tests and literature. And finally, a LCA was prepared to compare the carbon emissions and sequestration of three management processes of green waste; use as ADC, composting, and use as biofuel.

Dissertation Organization

This dissertation is organized in five chapters. Chapter 2 provides background information on regulations and standards for types of landfill covers. Also, it presents a literature review on alternative landfill covers and life cycle assessment (LCA) in solid waste management.

Chapter 3 presents the results of the geotechnical testing of mulch in the laboratory, the slope stability modeling, and compaction testing of cover material. Results demonstrate that, due to the relatively high porous nature of mulch, it is expected to act poorly in controlling infiltration. However mulch is expected to promote good aeration when used as landfill covers, which increases the efficiency of methane oxidation. Modeling results show greater stability for mulch covers than soil covers due to the angularity of mulch particles which increased the shear strength and cohesion of mulch. Compaction testing shows that mulch, under vertical stress of waste overburden and compactors weight, is expected to provide volume savings to landfills. This work has been accepted and presented at the 2010 *Global Waste Management Symposium* and will be submitted to *Geotechnical and Environmental Engineering.*

Chapter 4 presents the results of the field testing of mulch covers as landfill intermediate covers. Results show that mulch covers provide greater capacity for VOC oxidation and more volume reduction than soil and soil/mulch mixture covers. Mulch covers were found to provide no significant infiltration control. Percent VOC removal in mulch layers was found to decline with increase in loading; suggesting nonlinear Monod-like kinetics. However there were not enough removal data points to identify the point of oxidation saturation (or maximum removal capacity). Daily cover is not expected to provide VOC control because of the 200-day lag period observed in the field. This work will be submitted to the journal *Waste Management.*

Chapter 5 presents a LCA that compares three management processes of vegetative mulch; use as alternative daily cover (ADC), composting, and use as biofuel, in terms of global warming impacts. In this LCA, two approaches in accounting for greenhouse gas (GHG) were followed; one that accounts only for carbon sequestration and methane emissions, and the other additionally accounting for biogenic emissions. Results following the two approaches were dramatically different. Accounting only for non-biogenic GHG emissions showed that use of mulch as biofuel actually is the best environmental practice providing exceptional GHG emission offsets, while landfilling generated positive net GHG emissions. On the other hand, when carbon sequestration and biogenic emissions are accounted for, only landfilling provided GHG emission offsets, while using mulch as biofuel generates positive net GHG emissions. This work will be submitted to the *Sardinia Symposium.*

Chapter 6 presents the main conclusions and recommendations of this research. Appendices provide description of the quality control and quality assurance (QC/QA) plan that was followed in order to ensure the reliability of the results, as well as to minimize errors while collecting and analyzing the samples.

References

Bary, A. I., Cogger, C.G., Sullivan, D.M., Myhre, E.A. 2005. “Characterization of fresh trimmings for agricultural use”. Bioresource Technology 96 (2005) 1499-1504.

Benson, C., Daniel, D., Boutwell, G. (1999), Field Performance of Compacted Clay Liners, J. of Geotech. and Geoenvironmental Eng., ASCE, 125(5), 390-403.

Bracci G., Paci B., Giardi M. (1995). “Paper mill sludge used a daily cover in landfills. Proceedings of Fifth International Landfill Symposium, Sardinia, 1995”. 897–904.

Bradley A.D., Cook D.J., Edwards J.S., Johnston A.G., Linforth R.S., Taylor A.J. (2001). “The control and measurement of landfill odours. Proceedings of Eighth International Landfill Symposium, Sardinia, 2001”. 681–690.

Carson D.A. (1992). “Municipal solid waste landfill daily cover alternatives, Geotextiles and Geomembranes”. 11:629–635.

Cogger, C., Bary, A., Sullivan, D. (2002). “Fertilizing with yard trimmings”. Washington State University.

Florida Department of Environmental Protection, FDEP. “62-701.500 Landfill Operation Requirements”.

Hancock J.S, Newman S.J., Chadwixk B.R. (1999). “Mulched woody material mixtures: a improved performance daily cover. Proceedings of seventh International Landfill Symposium, Sardina, 1999”. 365-372.

Haughey, R. (2001). “landfill alternative daily cover: conserving air space and reducing landfill operating cost”. Waste Management and Research 19 (2001), pp. 89–95.

Humer, M., Lechner P. (1999). “CH4 oxidation in compost cover layers on Landfills. Proceeding of Seventh International Waste Management and Landfill Symposium, Cagliari, Italy. 1999”.

Hurst, C., Longhurst, P., Pollard, S., Smith, R., Jefferson, B., Gronow, J. (2005). “Assessment of municipal waste compost as a daily cover material for odour control at landfill sites”. Environmental Pollution, Vol 135, p (171-177).

Muntoni A., Cossu R. (1997). “Influence of compost covers on landfill gas surface emissions. Proceedings of Sixth International Landfill Symposium, Sardinia, 1997”. 115–125.

Shimaoka T., Miyawaki K., Hanashima M., Tsuji H., Ito H. (1997). “Impact of daily cover soil on the stabilisation of a landfill. Proceedings of Sixth International Landfill Symposium, Sardinia, 1997”. 341–350.

Uhlar-Heffner, G., Reed, B., Jackson, S. 1998. “Dealing with yard trimmings in the Puget Sound”. Biocycle 30 (5), 32–36.

U.S Environmental Protection Agency /Office of Solid Waste (2008). “Municipal Solid Waste in the United States: 2008 Facts and Figures”.

CHAPTER 2: BACKGROUND INFORMATION

Landfill Covers

There are three types of landfill covers usually categorized according to their function; daily, intermediate and final landfill cover. The daily landfill cover is a layer usually of soil or other alternative cover material that is frequently placed on top of the landfill at the end of each day to restrict the amount of windblown debris, odors, rodents, and insects on the site and controls fire hazards (Hughes et al., 2002). The intermediate cover is placed on the top areas of a landfill that will not be used for a long period of time (90 days according to State of Florida regulations). Intermediate landfill covers should have low hydraulic conductivity and sufficient mechanical stability. Final covers are meant to seal the landfill. The main objectives of the final cover are to minimize the infiltration of water from rainfall/snowfall after the landfill has been completed, limit the uncontrolled release of landfill gases, limit the potential for fires, and provide a suitable surface for the re-use of the site (Ammar, 2000). Below is a more detailed description of the different types of covers and their functions.

Daily Landfill Cover

A layer usually of soil or other alternative cover material is placed on top of the landfill at the end of each day to restrict the amount of windblown debris, odors, rodents, and insects on the site and controls fire hazards (Hughes et al., 2002). The Department of Environmental Protection (Department) Solid Waste Management Facilities Rule, Chapter 62-701, Florida Administrative Code (F.A.C.), contains requirements for managing solid waste. Included in this rule are requirements for initial cover and alternate initial cover materials (AICMs) at solid waste landfills. Rule 62-701.200(53), F.A.C. requires placement of a 15-cm layer of compacted earth to cover an area of solid waste before placement of additional waste, intermediate cover, or final cover. The term also allows other material or thickness, approved by the Department, provided that disease vector breeding, animal attraction, moisture infiltration, fire potential, blowing litter and odors are minimized, and landfill appearance is improved.

With increased levels of urbanization and consequential location of landfills in close proximity to highly populated areas, there has been an increasing intolerance to odor. Landfill gas consists of up to 65% v/v CH_4 and 35% v/v CO_2, both of which are considered to be greenhouse gases contributing to global climate change (Allen et al., 1997). Trace volatile organic compounds represent less than 1% v/v of landfill gas, however, these compounds are often odorous (Bradley et al., 2001). Daily cover is effective in controlling gas emissions and consequently it is important to reduce local impacts and complaints.

Soil erosion is considered to be the biggest contributor to non-point source pollution in the United States (Cabrera et. al. 2006). According to the ASTM D6523-00, daily landfill cover should control erosion when a 15-cm soil and/or other alternative material layer is placed on the surface of the waste. Use of surface-applied organic amendments has been proven to reduce runoff and erosion (Meyer et al., 1972; Laflen et al., 1978; Vleeschauwer et al., 1978; Foster et al., 1985; Gilley and Risse, 2001). Organic material placed on top of soil will intercept and dissipate energy of falling rain drops, reduce soil surface crusting, increase surface roughness and storage, and improve soil quality resulting in increased infiltration and reduced soil erodibility (Risse et. al. 2005).

Intermediate Landfill Cover

Intermediate landfill covers are usually 60 cm of clayey soil and another 15 cm of top soil (Bagchi 2003), the cover should have low hydraulic conductivity and high mechanical stability. Leachate horizontal and vertical flows can be controlled through the compaction of the material used as landfill intermediate cover by minimizing both the hydraulic conductivity and the pore size (Jang et al., 2002). Intermediate landfill covers must have sufficient shear strength to resist sliding on the slope and have tensile capacity large enough to prevent cracking during local subsidence (Benson and Othman, 1993).

Final Landfill Cover

Final covers usually consist, from top to bottom, of 1 m thick vegetation and supporting soil layer, a 15 cm thick filler and drainage layer, a 60 cm thick clay layer as a hydraulic barrier, a 15 cm thick layer of gravel as a foundation for the hydraulic barrier, and a gas control layer. EPA regulations require that the final cover be less permeable than the intermediate and daily covers (Vesilind et al. 2002). To meet final cover requirements, Hathaway and McAneny (1987) and Koerner and Daniel (1992) suggest the landfill cover must be able to withstand climatic extremes without surface cracking, resist water and wind erosion, resist landslides and the effects of differential settlement, support haulways for the placement of future cover, resist deformations caused by earthquakes, withstand alteration caused by constituents in the landfill gases and resist disruption caused by plants, burrowing animals.

Alternative Daily and Intermediate Landfill Covers

Title 40, Part 258 of the Code of Federal Regulations, Solid Waste Disposal Facility Criteria, commonly referred to as Subtitle D, became effective on October 9, 1993. It establishes minimum criteria for solid waste disposal facility siting, design, operations, groundwater monitoring and corrective action, and closure and postclosure maintenance, while providing EPA-approved state solid waste regulatory programs flexibility in implementing the criteria.

40 CFR 258.21(b) allows the director of an approved state to approve alternative materials of an alternative thickness if the owner or operator demonstrates that the alternative material and thickness will control disease vectors, fires, odours, blowing litter, and scavenging without presenting a threat to human health and the environment. However, 40 CFR 258.21(b) does not state how the demonstration is to be made.

Many states, in revising their state regulations to incorporate Subtitle D requirements, simply adopted the Subtitle D language. Other states, such as Texas and California, have adopted specific requirements for ADC equivalency demonstrations (Haughey 2001).

In Florida, the department of Environmental Protection (DEP), in its Solid Waste Management Facilities Rule (Chapter 62-701, Florida Administrative Code (F.A.C.), states in section 200(53) the requirements for an ADC:

"…the term "initial cover" also includes other material or thickness, approved by the DEP, that minimizes disease vector breeding, animal attraction, and moisture infiltration, minimizes fire potential, prevents blowing litter, controls odors, and improves landfill appearance". In approving an ADC, information about the new material such as general product description, flammability information, chemical characterization, leaching potential and product performance is required by the Solid Waste Section in Tallahassee. If the review is satisfactory then the field testing of the ADC is authorized at landfills. However, final approval for use of the new material as ADC is left to the judgment of the district offices of the DEP.

General product description includes the identification of the main ingredients of the product including hazardous chemicals, description of the how the product is manufactured, physical/chemical characteristics, physical hazards, health hazards, proper handling, and description of how the ADC is to be used on landfills.

Flammability information has to demonstrate that the material is not flammable or is self-extinguishing (it will not continue to burn when an external source of flame is removed) This demonstration is provided by conducting flammability tests on representative samples of the material as it would be expected to exist in actual landfill use. Tests which may be appropriate are:

1. ASTM D4982-89, Standard Test Methods for Flammability Potential Screening Analysis of Waste,
2. ASTM E1354, Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products, Using an Oxygen Consumption Calorimeter,
3. NFPA 701, Fire Tests for Flame Resistant Textiles and Films, and
4. FMVSS 302, Flammability of Interior Materials of Cars, Trucks, Multipurpose Passenger Vehicle Buses.

Chemical characterization is achieved through obtaining a representative sample of the ADC, as it is expected to be used at a landfill, and analyze it using the Toxicity Characteristic Leaching Procedure (TCLP), EPA Method 1311. The resulting extract must be analyzed for the parameters contained in 40 CFR 261.24 and with the resulting concentrations compared to their corresponding EPA regulatory levels. If any of the parameter concentrations in the TCLP test exceed EPA's regulatory levels, then the ADC will not be allowed for use at Florida landfills.

Parameters analyzed are the eight Resource Conservation Recovery Act (RCRA) metals (Arsenic, Barium, Cadmium, Chromium, Lead, Mercury, Selenium, and Silver), aluminum, antimony, beryllium, nickel, sodium, and thallium using the appropriate test methods for these metals contained in EPA publication SW-846, volatile organic compounds using EPA Method 8260; and semivolatile organic compounds using EPA Method 8270.

Leaching potential is analyzed through obtaining a representative sample of the ADC, as it is expected to be used at a landfill, and evaluating the cover's leaching potential using the Synthetic Precipitation Leaching Procedure (SPLP), EPA Method 1312. The extract prepared with this procedure must then be analyzed for the same elements and compounds as in the chemical characterization test above. The DEP is also concerned about the potential of runoff from the use of ADC polluting the landfill's surface water system. To evaluate this potential impact, the results of the SPLP testing required above must be also compared to the DEP's surface water standards and criteria.

Product performance information should be provided from landfills that used the ADC describing how the cover minimized the vector breeding, animal attraction, and moisture infiltration. They should also provide a description of how the ADC will prevent blowing litter, control odors, improve the landfill appearance, and what is the chance of adversely impacting birds or other wild life should they come into contact with it.

Investigating the capacity of alternative daily cover materials to attenuate odorous emissions can be undertaken using olfactometry, or via the quantification of potentially odorous compounds using chemical analysis. The latter provides quantitative on the presence of potentially odorous emissions. In contrast, olfactometry provides information on the odor threshold and thus potential sensory impact from the perception of the individual. Therefore, ideally a combination of the two techniques would be required to assess the efficiency of a material to reduce the release of odorous compounds into the atmosphere (Hurst et. Al 2004).

On a nation wide scale, EPA developed the Alternative Cover Assessment Program (ACAP) in 1997. This national program, supervised by National Risk Management Research Laboratory (NRMRL) researchers, was the first field-scale, side-by-side comparison of traditional and alternative covers. With help of private and public partners, the ACAP researchers in 14 communities over a 6-year period examined the water infiltration passing through the test cover systems generating the world's largest body of data on landfill cover performance.

Materials for alternative landfill covers investigated to date include paper mill sludge, fly ash, mulched wood material, tarps, and foams, shredder fluff (Bracci et al., 1995; Bradley et al., 2001; Carson, 1992l; Hancock et al., 1999; Shimaoka et al., 1997). Haughey (2001) classified alternative into three broad categories according to their way of application; blankets, sprays, and waste materials.

Blanket ADCs are usually tarps providing a solid barrier to odors and vectors. Current tarps have been designed to resist or minimize punctures and tears; they can be laid out over the working face by hand, with a bulldozer, or with specially designed equipment that can roll out the tarp each night and remove it in the morning (Merrill 2008).

Sprays ADCs fall into two major categories, slurries and foams. Slurries are solids like newspaper, mixed paper, wood fibre, cement kiln dust, or fly ash mixed with water and sprayed onto the landfill working face. Ash has been used as an alternative daily cover and is a good hydraulic barrier in a typical landfill cover or liner (Okoli and Balafoutas, 1999). Non-hardening foam is applied directly to the working face of the landfill to create a temporary barrier that can last from one to three days, depending on weather conditions and application rates. The foam may be applied either with a truck-mounted device or a self-propelled unit, under a variety of temperature and weather conditions. The foam retains its resiliency and dissolves once heavy equipment begins working over waste (Merrill 2008). Waste materials that are currently being used as ADC include yard waste, sludge, auto shredder waste, shredded tires, cement kiln dust, and impacted soil.

Life Cycle Assessment of Solid Waste Management (SWM) Processes

The concept of LCA has been applied in the field of solid waste management to investigate the benefits and environmental impacts of solid waste management (SWM) processes. LCAs focused on management options such as landfilling, incineration, recycling, composting, anaerobic biodegradation, and gasification; analyzing and comparing their various effects on global warming, air quality, ground and surface water quality, and non-renewable energy consumption. Assessments vary in their boundary dimensions (waste components, MSW management processes, environmental impacts and time) and in the assumptions and models that the entire study is based upon.

Finnveden et al. (2004) produced a LCA that compares recycling, anaerobic digestion, composting, incineration and landfilling specifically in terms of their effects on energy consumption, Green House Gas (GHG) emissions, and acidification. However, there was no consideration of the carbon sequestration achieved through landfilling and composting. Only the fate of combustible and compostable fractions of waste was considered in this study. Recycling of paper and plastic materials was found to be favorable in terms of energy consumption and GHG emissions. Incineration, in general, was found to be favorable over landfilling in terms of energy use, GHG emissions.

Cabaraban et al. (2007) conducted a LCA that compares aerobic in-vessel composting with bioreactor landfilling of food waste, yard waste, and the soiled paper fraction. The study was focused mainly on energy recovery, GHG emissions, water emissions contributing to aquatic toxicity, air emissions contributing to human toxicity, and on the economic feasibility of the two processes. It was found that bioreactor landfill is a favourable option over in-vessel composting in terms of cost, overall energy consumption, and air-borne and water-borne emissions.

Haight (2005) compared biogasification and composting with traditional landfilling of the biodegradable fraction of the waste using LCA. Impacts considered were energy consumption (or recovery), residue recoveries and emissions to air and water. Results showed that anaerobic degradation of the organic fraction of waste and the resulting energy recovered makes this process superior to composting.

Kaplan et. al. 2008 evaluated the SWM taking place in the state of Delaware from economic and GHG emission point of view and compared various scenarios of management that include recycling at different levels and composting using the EPA Decision Support Tool (DST).

However, while there are benefits associated with compost as a product in certain applications, Kaplan et. al. did not calculate offsets achieved in using compost instead of chemical fertilizers.

Komilis and Ham (2004) worked on a Life Cycle Inventory (LCI) for composting facilities that handled different fractions of waste including yard waste, food waste and mixed paper. The study focused on total management costs, precombustion and combustion energy requirements and consumption and production of 29 selected materials. The least expensive facility was the one handling only yard waste with a cost of $15/ton yard waste.

Carbon Sequestration in Landfills

Atmospheric levels of CO_2 have risen from pre-industrial levels of 280 parts per million (ppm) to present levels of 375 ppm (Department of Energy 1999). Evidence suggests this observed rise in atmospheric CO_2 levels is due primarily to expanding use of fossil fuels for energy.

Landfill gas is comprised of two major GHG, CO_2 and CH_4. Methane, however, remains in the atmosphere for approximately 9-15 years and is over 21 times more effective in trapping heat in the atmosphere than carbon dioxide CO_2 over a 100-year period (http://epa.gov/methane/). In the US, landfills are the second largest anthropogenic source of carbon (as CH_4) accounting for 23% of total US methane emissions for a CO2 equivalent of 132.9 Tg in 2007 (2009 Draft U.S. Greenhouse Gas Inventory Report). Reported landfill gas production rates vary from 0.12 to 0.41 m^3/kg dry waste (Pohland and Harper, 1985).

Yard waste is almost 13% of the total MSW that goes into the landfill and is approximately 50% carbon (Tchobanoglous et al, 1993). The two basic metabolic pathways for decomposition or degradation of organic wastes are aerobic (with oxygen) and anaerobic (in the absence of oxygen). Aerobic and anaerobic systems might be generally represented by Equations 2.1 and 2.2 respectively (Robinson W. 1986):

$$\text{Organic in Solid Waste} + O_2 \longrightarrow \text{Bacterial Cells} + CO_2 + H_2O + \text{Energy} \quad (2.1)$$

$$\text{Organic in Solid Waste} \longrightarrow \text{Bacterial Cells} + CO_2 + CH_4 + \text{Energy} \quad (2.2)$$

As can be seen in Equations 2.1 and 2.2, the carbon in landfilled yard waste has basically four possible fates; (1) production of CO_2 resulting from biodegradation, (2) production of CH_4 as the result of anaerobic biodegradation, (3) sequestered when yard waste is applied as mulch and buried as daily and intermediate covers in landfills, and (4) other less significant fates such as conversion to biomass (bacterial cells) and dissolution in leachate (SWANA 2006).

Anaerobic conditions normally prevail in landfills which are not conducive to the decomposition of lignin or to cellulosic material protected by lignin. Consequently, much of wood and vegetative waste, which is primarily lignin and cellulose, will remain in the landfill for very long periods of time potentially making the use of mulch as alternative daily cover in landfills a sink for carbon (Barlaz M. 1998). It is estimated that approximately 50% of the yard waste placed in landfills does not degrade (Barlaz, 1989). Thus, while landfills tend to contribute large amounts of greenhouse gases, to some extent they offset these emissions through carbon sequestration.

In order to quantify the carbon sequestration in landfills, the percentage of carbon degradation in organic waste must be estimated. The National Council for Airstream Improvement Inc. (NCASI) recommends that a carbon storage factor of 0.85 tons carbon sequestered per ton of carbon material landfilled be used for estimating carbon sequestration of wood products in landfills. Micales and Skog (1997) used methane potential for different types of materials in a temperate environment to calculate percent of carbon potentially released from landfilled wood and paper products. They estimated that an average of 26% of carbon from paper and 0% to 3% from wood is released as methane and carbon dioxide after landfilling. Barlaz (1997) measured carbon sequestration for four paper categories under anaerobic conditions in the laboratory. The USEPA (2002) have relied on this experiment for the development of carbon storage factors (CSF) in landfills; 0.38 tons of carbon sequestered per ton of dry material (wood and wood products) is recommended for estimating carbon sequestration in landfills.

Carbon Sequestration of Mulch and compost

Both the application of compost on agricultural soils and the use of mulch in landfill covers will sequester (store) a fraction of the carbon after biological degradation. Favoino and Hogg (2008) studied the potential for composting to both sequester carbon and to mitigate GHG emissions using LCA. They concluded that composting could reduce GHG by reducing the application of mineral fertilizers, pesticides and peat. Calculations show that 0.15% increase in organic carbon in arable soils in a country the size of Italy would provide the same amount of carbon sequestration in soil that is currently emitted into the atmosphere in a period of one year through the consumption of fossil fuels in that country (Sequi P. 1998).

However, Favoino and Hogg conclude that composting is a time-limited sequestration tool since over a relatively long time frame almost all the organic carbon will be oxidized and emitted to the atmosphere. They also argue that a conventional LCA fails to indicate the rate at which both GHG emissions and carbon sequestration would impact (or benefit) the climate. They state that the rate of degradation and GHG emissions from a composting activity will be relatively high at the beginning of the process, slowing down at the maturation phase, and declining to a minimum value once applied to the soil. The exact rates of degradation, however, will vary widely based on the different types of organic matter found in yard waste (Smith et al 2001).

USEPA suggests life times of 20 to 2000 years for various types of soil organic carbon. Other studies avoided the long-term analysis and based their calculations on the fact that green waste is composed mainly of recalcitrant lignin and slowly decomposing cellulose, estimating that 50% of the carbon in yard waste will be sequestered in landfills (Huber-Humer 2004, Zinati et al. 2001; Barlaz 1998; Bramryd 1997; Bogner 1992).

References

Allen M.R., Braithwaite A., Hills C.C. (1997). “Trace organic compounds in landfill gas at Seven U.K. waste disposal sites”. Environmental Science Technology. 31:1054–1061

Ammar A.M. (2000). “Designing sustainable landfill for Jeddah City, Saudi Arabia”. Bulletin of Engineering Geology and the Environment 58

Bagchi A. (2003). “Design of Landfills and Integrated Solid Waste Management”. John Wiley & Sons Inc

Barlaz, M, Ham, R., Schaefer, D. (1989). “Mass-balance analysis of anaerobically decomposed refuse” J. Environ. Engin., 115, 1088-1102

Benson C.H., Majdi A.O. (1993) “Hydraulic and Mechanical Characteristics of a Compacted Municipal Solid Waste Compost”. Waste Management & Research. 11(2):127-142.

Bogner, J.E. (1992). “Anaerobic burial of refuse in landfills: Increased atmospheric methane and implications for increased carbon storage”. EC01. Bull.

Bracci G., Paci B., Giardi M. (1995). “Paper mill sludge used a daily cover in landfills. Proceedings of Fifth International Landfill Symposium, Sardinia, 1995”. 897–904.

Bradley A.D., Cook D.J., Edwards J.S., Johnston A.G., Linforth R.S., Taylor A.J. (2001). "The control and measurement of landfill odours. Proceedings of Eighth International Landfill Symposium, Sardinia, 2001". 681–690.

Bramryd, T. (1997). "An Integrated System for Energy and Nutrient Extraction from Solid Wastes through Treatment in Landfill Reactor Cells". Proceedings of the Sixth International Landfill Symposium, Sardinia, Italy, pp. 324–330.

Barlaz, M. (1997). "Biodegradative Analysis of Municipal Solid Waste in Laboratory-Scale Landfills." U.S. Environmental Protection Agency Report #EPA 600/R-97-071, Washington, D.C.

Barlaz, M. (1998). "Carbon storage during biodegradation of municipal solid waste components in laboratory-scale landfills". Global biogeochemical cycles. Vol. 12, No. 2. 373-380.

Bradley A.D., Cook D.J., Edwards J.S., Johnston A.G., Linforth R.S., Taylor A.J. (2001). "The control and measurement of landfill odours. Proceedings of Eighth International Landfill Symposium, Sardinia, 2001". 681–690.

Cabrera M.L., Coleman D.C., Faucette L.B. Jordan C.F. Risse L.M, West L.T. (2006). "Vegetation and soil quality effects from hydroseed and compost blankets used for erosion control in construction activities". Journal of Soil and Water Conservation (Nov 2006).

Cabaraban, M., Khire, M., Alocilja, E. (2008). "Aerobic in-vessel composting versus bioreactor landfilling using life cycle inventory models". Clean Techn Environ Policy 10:39–52.

Carson D.A. (1992). "Municipal solid waste landfill daily cover alternatives, Geotextiles and Geomembranes". 11:629–635.

Favoino, E., Hogg, D. (2008). "The potential role of compost in reducing greenhouse gases". Waste Management and Research. 26: 61–69

Finnveden G., Johansson J., Lind P., Moberg A. (2004). "Life Cycle Assessments of Energy from Solid Waste". Journal of Cleaner Production. 13(3):231-240.

Foster G.R.,Young R.A., Romkens M.J.M, Onstad C.A. (1985). "Process of soil erosion by water". In: Follet, R.F. and B.A Stewart. Soil erosion and crop productivity. ASA. CSSA and SSSA, Madison WI. 137-162.

Gilley J.E., Risse L.M. (2001). "Runoff and soil loss as affected by the application of manure". 43(6):1538-1588.

Haight, M. (2005). “Assessing the environmental burdens of anaerobic digestion in comparison to alternative options for managing the biodegradable fraction of municipal solid wastes”. Water Science & Technology Vol 52 No 1-2 pp 553–559.

Hancock J.S, Newman S.J., Chadwixk B.R. (1999). “Mulched woody material mixtures: a improved performance daily cover. Proceedings of seventh International Landfill Symposium, Sardina, 1999”. 365-372.

Hathaway A.W., McAneny C.C. (1987). “An in-depth look at landfill covers”. Waste Age. 17(8).

Haughey, R. (2001). “landfill alternative daily cover: conserving air space and reducing landfill operating cost”. Waste Management and Research 19 (2001), pp. 89–95.

Huber-Humer, M., (2004). “International research into landfill gas emissions and mitigation strategies – IWWG working group [CLEAR]”. Waste Manage. 24, 425– 427.

Hughes K.L., Hughes A.D., Joe E.H. “Landfills: Science and Engineering Aspects”. Ohio State University, Extension Fact Sheet: Community Development.CDFS-137-05

Hurst, C., Longhurst, P., Pollard, S., Smith, R., Jefferson, B., Gronow, J. (2005). “Assessment of municipal waste compost as a daily cover material for odour control at landfill sites”. Environmental Pollution, Vol 135, p (171-177).

Jang Y.S, Kim W., Lee S.I. (2002). “Hydraulic properties and leachate level analysis of Kimpo metropolitan landfill, Korea”. Waste Management. 22(3):261-267.

Kaplan P. O., Ranjithan S. R., Barlaz M. A. (2008). “Use of Life-Cycle Analysis to Support Soil Waste Management Planning for Delware”. Environmental Science & Technology.

Komilis, D., Ham, R. (2004). “Life-cycle inventory of municipal solid waste and yard waste windrow composting in the United States”. Journal of Environmental Engineering 130 (11)1390–1400.

Koerner R.M., Daniel D.E. (1992). “Better cover-ups”. Civil Eng 62(5).

Laflen J.M., Baker J.L., Hartwig R.O., Buchele W.A., Johnson H.P. (1978). “Soil and water loss from conservation tillage system”. Trans. ASAE. 21:881-885.

Merrill L. (2008). “Covering Their Tracks. Landfills turn to daily covers such as tarps and foams to conserve airspace” Waste Age.

Meyer L.D., Johnson C.B., Foster G.R. (1972). “Stone and woodchip mulches for erosion control on construction sites.” Journal Soil Water Conserve. 27:264-269.

Micales J.A, Skog K.E. (1997). “The decomposition of forest products in landfills”. International Biodeterioration and Biodegradation. 39(2-3):145-158.

National Council for Air and Stream Improvement (NCASI), http://www.ncasi.org.

Okoli, R., Balafoutas, G. (1998). “Fixation of airborne sand drifting using a bottom ash of sludge cake”. Journal of Arid Environments, 39, 79-91.

Pohland F.G., Harper S.R. (1985). “Critical Review and Summary of Leachate and Gas Production from Landfills”. EPA/600/2-86/073, US Environmental Protection Agency, Cincinnati.

Risse L.M., Faucette L.B., Gaskin J.W., Jordan C.F., Cabrera M., West L.T. (2005) “Field evaluation of compost and mulches for erosion control”. Proceedings of the 2005 Georgia Water Resources Conference.

Robinson W. D. (1986). “The Solid waste handbook: a practical guide”. Wiley-Interscience

Sequi, P., Tittarelli, F. (1998). “Outlook on perspectives for compost in Italy. In: Federal Ministry for the Environment”. Youth and Family Affairs, (ed.) EU Symposium Compost–Quality Approach in European Union. Wien, 29-30 October 1998, pp 161-167

Shimaoka T., Miyawaki K., Hanashima M., Tsuji H., Ito H. (1997). “Impact of daily cover soil on the stabilisation of a landfill. Proceedings of Sixth International Landfill Symposium, Sardinia, 1997”. 341–350.

Smith, A., Brown, K., Ogilvie, S., Rushton, K., Bates, J. (2001) “Waste Management Options and Climate Change-Final report to the European Commission”. DG Environment, Brussels, Belgium.

SWANA (2006). “Analysis of Carbon Sequestration in the Cedar Hills Regional Landfill”. SWANA's 21st Annual Pacific Northwest Regional & Canadian Symposium April 5-7, 2006, Richmond, B.C., Canada

Tchobanoglous G., Theisen H., Vigil S. (1993). “Integrated Solid Waste Management: Engineering Principles and Management Issues”. McGraw Hill, Inc., USA.

U. S. Department of Energy, Energy Efficiency and Renewable Energy Clearinghouse, Biomass Cofiring: A Renewable Alternative for Utilities.

U. S. Environmental Protection Agency (2002). “Solid waste management and greenhouse gases: a life-cycle assessment of emissions and sinks”. Washington, DC: US Environmental Protection Agency; p. 77–78.

U. S. Environmental Protection Agency (2010). “Inventory of US greenhouse gas emissions gas emissions and sinks 1990-2008”.

Vesilind P.A., Worrell W. Reinhart D.R. (2002). “Solid Waste Engineering”. Brooks/Cole, Pacific Grove, Ca, USA.

Vleeschauwer D.D., Boodt M.D. (1978). “The comparative effects of surface applications of organic mulch versus chemical soil conditioners on physical and chemical properties of the soil and on plant growth.” Catena 5:337-349.

Zinati, G., Li, Y., Bryan, H. (2001). “Utilization of compost increases organic carbon and its humin, humic and fulvic acid fractions in calcareous”. Soil Compost Sci. Util. 9. pp. 156–162.

CHAPTER 3: LABORATORY ASSESSMENT OF VEGETATIVE MULCH

Introduction

Management of yard waste is a significant challenge in the US, where, in 2008, yard waste was reported to be 13.2% of the 250 million tons of municipal solid waste (MSW) (USEPA, 2008). According to Subtitle D of the Resource Conservation and Recovery Act (RCRA) codified in the Code of Federal Regulation (CFR) 258.21 Section (a); landfill owners and operators are required to cover the active face of the landfill with a minimum of 15 cm of earthen material at the end of every day (or at more frequent intervals if necessary) to control disease vectors, fires, odors, blowing litter, and scavenging. Florida regulations require an intermediate cover in addition to the 15-cm daily cover to be applied and maintained within seven days of cell completion if additional solid waste will not be deposited within 180 days of cell completion (62-701.500 Landfill Operation Requirements, Florida Department of Environmental Protection, FDEP). Many landfill operators must import cover soil from outside of the facility, increasing operating costs. Section CFR 258.21(b) allows the use of alternative cover materials if the landfill owner or operator demonstrates that the alternative material and thickness will function the same as a soil cover and does not present a threat to human health and the environment.

Because of its volume and potential use as a soil amendment, the disposal of yard waste in lined landfills is banned in most states. Consequently, yard waste is frequently composted or mulched in preparation for recycling. Composting involves the aerobic biological degradation of ground yard waste to a soil-like material which is a beneficial additive to soils. Mulching, on the other hand, involves size reduction and homogenizing without biological processing, requiring less time, land, quality control, and processing, and thus, lower cost in comparison to compost production. However, spontaneous fire in vegetative mulch storage piles is considered an infrequent but serious problem.

Background

In 2001, the California Assembly passed a bill that allows the use of yard waste as alternative daily cover (ADC) as part of the recycling effort of a community (Haughy 2001). Currently, an estimated 2.1 million tons of source-separated yard waste are shredded and used annually as ADC in landfills (Stephens, 2007; Kaufman and Themelis, 2009). Composted waste has been used as daily and intermediate landfill covers and studies have assessed its ability to control gas emissions and rain infiltration into the landfill.

Benson and Othman (1993) showed that compacted municipal solid waste (MSW) compost with hydraulic conductivity as low as 2×10^{-10} m/s could be used effectively as an alternative material to clay in landfill covers or liners because it had more resistance to cracking caused by desiccation and freeze-thaw and more shear strength than compacted clay. Hurst et al. (2004) showed that MSW compost covers have the ability to reduce odorous emissions from landfill sites by up to 97% and Muntoni and Cossu (1997) reported the ability of compost to remove chlorinated hydrocarbons and sulfur compounds from gaseous emissions.

Humer and Lechner (1999) found that MSW compost covers were capable of methane oxidation and. Stern et al. (2007) also found that biocovers composed of composted yard waste have a 64% average potential for oxidizing methane and recorded locations where compost covers provided 100% methane oxidization. Barlaz et al. (2004) compared methane emissions from landfill cells covered with an intermediate soil cover with a biologically active (yard waste compost) intermediate cover. Although the soil covers generally performed well, high emissions were detected in several areas which were associated with desiccation cracks, while the bioactive cover had no cracks. It was found that biocovers offered advantages over traditional soil covers because of their increased organic content and associated moisture holding capacity, making them less susceptible to cracking and erosion relative to clay.

A layer consisting of 1.2 m of mature, well-structured compost overlaying a 0.3-0.5-m gravel layer was used as an intermediate biocover in a landfill in Austria between 1999 and 2002. This cover successfully controlled methane emissions and minimized leachate generation (Huber et al. 2008). Methane oxidation did not decline during winter for the biocover; whereas oxidation rates declined during colder seasons in conventional soil covers (Liptay et al. 1998, Chanton & Liptay 2000, Börjesson et al. 2001). Humer et al. (2004) demonstrated that a landfill cover material that is both fine textured and has sufficient porosity (e.g. sewage sludge mixed and composted with large wood chips) will promote good air diffusion from the atmosphere and sufficient retention time for methane oxidation.

It is anticipated that vegetative mulch could provide significant cost savings over soil or compost covers, allowing space recovery in landfills as it degrades over time, and result in carbon sequestration within the landfill related to recalcitrant organic fractions. Haaren et al. (2010) compared the use of yard waste as ADC to windrow composting using the Life Cycle Assessment (LCA) method, and found that the ADC option is more beneficial for the environment and is also a less costly means to dispose yard waste. This study investigates the use of vegetative mulch as daily and intermediate cover in landfills by assessing the behavior of mulch covers through laboratory testing and slope stability modeling. The behavior of vegetative mulch and soil mixtures was also investigated for comparison with mulch and soil covers. With the exception of particles size distribution and deformation tests, all analysis were conducted in duplicate.

Materials and Methods

Fresh mulch samples (Fresh Mulch) were collected at five Solid Waste Management Facilities (SWMF) in Florida to account for the potential diversity of yard waste composition across the state. Samples were collected over four seasons to account for changes in yard waste composition over time. Mulch is commonly stored in piles; therefore samples were collected from both the surface and one-meter deep into the pile and then were mixed following recommendations for sampling solid waste (provided in ASTM 523 1-92) that account for heterogeneity. To evaluate the effect of aging on mulch in covers, a sample (1Y-Mulch) was collected from a mulch intermediate cover that had been in place for one year. To analyze the properties of mulch and soil mixtures, fresh mulch and soil were combined in the laboratory

(Fresh Mix) at 1:1 (v/v) ratio. To evaluate the effect of aging on mixtures, 1:1 (v/v) mixtures of soil and mulch were collected from a one-year old (1Y-Mix) and a three-year old (3Y-Mix) mulch/soil landfill cover. A sample of Florida soil used for daily cover was also collected for comparison.

Material Characteristics

Vegetative mulch was generated at each SWMF by grinding yard waste to approximately 2.5-cm particles. Fresh mulch samples collected in this study were composed of branches, grass, and leaves as described in Table 1.

Table 1. Florida Landfill Fresh Mulch Sample Composition.

Fresh Mulch Sample	Branches	Leaves	Grass
	% by weight		
SWMF 1	92	5	3
SWMF 2-a	41	57	2
SWMF 2-b	88	6	6
SWMF 3	91	5	4
SWMF 4	90	5	5
SWMF 5	89	6	5

Direct shear tests were conducted on cover material, to obtain their internal friction angle and cohesion following ASTM D-3080 for direct shear tests of soil under consolidated and drained conditions. A 14-cm x 14-cm x 11-cm direct shear mold previously designed for shear tests on solid waste samples was used (Reinhart et al. 2003). Shear tests for cover material were conducted at the optimum moisture content and maximum compacted unit weight. The relationship between water content and dry unit weight of cover material (compaction curve) was determined by running the modified compaction test using a triaxial mechanical compactor with a 0.05-kN hammer (HUMBOLDT-H1336) in accordance with ASTM D-1557.

Sieve analysis was carried out for cover material following ASTM D-422, because less than 10% of the cover material samples passed the #200 sieve. Particle distribution was analyzed by passing 300-g samples through ten different sieves. Particle diameters at 10%, 30%, and 60% finer on the grain size distribution curve (D_{10}, D_{30}, and D_{60}, respectively) were used to calculate the Uniformity Coefficient (C_u) and the Coefficient of Curvature (C_c) using Equations 3.1 and 3.2. C_u and C_c were used to classify the type of cover material using the Unified Soil Classification System (USCS).

$$C_u = \frac{D_{60}}{D_{10}} \tag{3.1}$$

$$C_c = \frac{{D_{30}}^2}{D_{10} \times D_{60}} \tag{3.2}$$

The saturated hydraulic conductivity of the cover material was tested following ASTM D-2434. Specific gravity of the cover material was obtained following ASTM D854. Void ratio at optimum compaction was calculated using particle unit weight and optimum bulk unit weight values using Equation 3.3.

$$e = \frac{\eta}{1-\eta} \tag{3.3}$$

where,

$$\eta = 1 - \frac{\gamma_d}{\gamma_P}$$

$$\gamma_P = G_S \times \gamma_W$$

and,

e = Void ratio, unitless; η = Porosity, unitless; γ_d = Optimum dry bulk unit weight achieved during compaction testing, kN/m^3; γ_P = Particle dry unit weight, kN/m^3; G_S = Specific gravity, unitless; γ_W = Unit weight of water, kN/m^3 at 22 C^o.

Additional MSW will eventually be placed on top of daily and intermediate covers adding overburden, increasing bulk unit weights and decreasing void space of cover material. Due to the relatively large mulch particles, consolidation tests could not be conducted and instead the behavior of cover material was studied using a test which measures deformation of cover material under the application of increasing vertical confined stress. Specimens were placed in the same mold used for shear testing and vertical pressure was continuously applied on the surface of the mold. The Universal Testing machine (SATEC 5590-HVL), powered by a hydraulic pumping system to create tension, compression, bend/flex, and shear, was used to generate the required vertical stress which was directly measured utilizing a strain gage load cell.

The loading was controlled at a vertical deformation rate of 0.8 cm/min and was set to a maximum stress of 1000 kPa while pressure and deformation data were generated every 0.1 second. The weight of the test sample before testing was measured and initial bulk unit weight and porosity were calculated. Void ratio calculations at every stress point are shown in Equations 3.4-3.7.

$$V_\sigma = A \times D_\sigma \tag{3.4}$$

$$\gamma_{d\sigma} = \frac{W_S}{V_\sigma} \tag{3.5}$$

$$\eta_\sigma = 1 - \frac{\gamma_{d\sigma}}{\gamma_P} \tag{3.6}$$

$$e_\sigma = \frac{\eta_\sigma}{1-\eta_\sigma} \tag{3.7}$$

where,

V_σ = Volume of sample at stress σ, m^3; *A*= Area of the shear box, m^2; D_σ = Depth of sample in the shear box at stress σ, m; $\gamma_{d\sigma}$ = Bulk dry unit weight of sample at stress σ, kN/m^3; W_S = Weight of sample, kN; γ_P = Particle unit weight of sample, kN/m^3; σ = Applied vertical stress, kPa; e_σ = Void ratio at stress σ, unitless; η_σ = Porosity at stress σ, unitless.

Slope Stability Modeling

The engineering properties of the cover material acquired through the laboratory tests were used to analyze the stability of cover and MSW layers placed on landfill slopes. Cover layers 15, 30, and 45 cm in thickness were modeled at slopes of 1:3 and 1:4. Covers were modeled when both exposed and with overlaying MSW. A minimum factor of safety (FS) of 1.5 was assumed to be the acceptable limit in accordance with stability studies conducted on landfill slopes (Qian et al. 2002, Shafer et al. 2000).

A linear failure model was used to simulate the potential failure of exposed landfill covers. Koerner and Soong (2005) showed that, where the cover material slides with respect to the lowest interface friction layer, long continuous veneer covers on a slope have potential failure planes that are linear. Calculations of FS for the exposed covers were based on a modified stability analysis methodology described by Koerner and Hwu (1991) who evaluated a finite length slope with soil cover placed over a geomembrane. The linear failure model, as illustrated in Figure 1, was modified to evaluate a uniformly thick cover material placed over MSW.

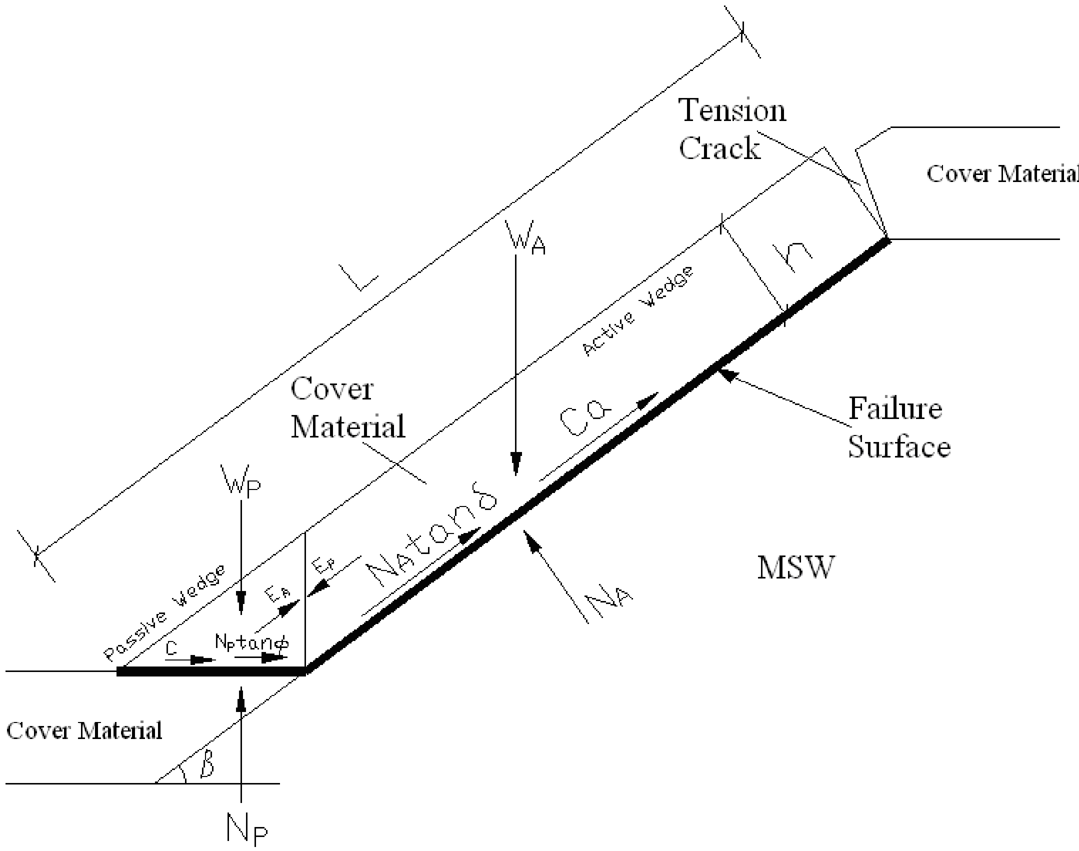


Figure 1. Potential Linear Surface of Failure at Interface between Cover and MSW (Adapted from Koerner and Hwu, 1991).

The model includes a passive wedge at the toe and has a tension crack at the crest. After balancing the vertical forces for the active wedge and the horizontal forces for the passive wedge and equating the two inter-wedge forces acting on the active and passive wedges, the FS against the cover sliding over MSW can be calculated using Equation 3.8.

$$FS = \frac{-b + \sqrt{b^2 - 4ac}}{2a} \qquad (3.8)$$

Where,

$a \quad = (W_A - N_A \cos\beta)\cos\beta$

$b \quad = -[(W_A - N_A \cos\beta)\sin\beta\tan\Phi +$

$$(N_A \tan\delta + C_a)\sin\beta\cos\beta + \sin\beta\,(C + W_P \tan\Phi)]$$

$c \quad = (N_A \tan\delta + C_a)\sin^2\beta\tan\Phi$

$W_A \quad = \gamma h^2 \left[\frac{L}{h} - \frac{1}{\sin\beta} - \tan\frac{\beta}{2}\right]$

$W_P \quad = \frac{\gamma h^2}{\sin 2\beta}$

$N_A \quad = W_A \cos\beta$

$C_a \quad = c_a\left(L - \frac{h}{\sin\beta}\right)$

$C \quad = \frac{ch}{\sin\beta}$

and,

β = Angle of the slope, c = Cohesion of cover material, kN/m^2; Φ = Friction angle of cover material, c_a = Adhesion between cover material and MSW, kN/m^2; δ = Interface friction angle between cover and MSW, h = Cover material thickness, mm; L = Length of the slope, m; W_A = Weight of the active wedge, kN; W_P = Weight of the passive wedge, kN; N_A = Effective force normal to the failure plane of the active wedge, kN; N_P = Effective force normal to the failure plane of the passive wedge, kN; γ = Bulk unit weight of the cover material, kN/m^3; C_a = Adhesive force between cover material of the active wedge and MSW, kN; C = Cohesive force along the failure plane of the passive wedge, kN.

Adhesion and interface friction angle between the cover material and MSW were obtained by conducting direct shear tests according to ASTM D-5321 where the lower half of the shear box was filled with MSW and the upper half with cover material. A synthetic MSW was prepared based on the composition of municipal solid waste in the United States (EPA 2007). The MSW sample was tested at moisture content of 25% by weight, the moisture of MSW typically arriving at a landfill (Vesilind et al. 2002).

The computer software program SLOPE/W developed by GEO-SLOPE International Ltd. was used to model slope stability for buried cover material. The software uses the theory of limit equilibrium of forces and moments to compute the FS against failure, and allows stability analysis of both block and circular failure modes. Such soil-based slope stability analysis programs have been found to be suitable for modeling landfill slopes as the waste is assumed to behave like a cohesive soil (Shafer et al. 2000).

A block failure model was used to simulate the expected failure of a layer of cover material between two MSW layers since failure is assumed to occur due to the weight of the MSW block acting as a driving force along the interface of waste and the underlying cover layer (Blight 2006, Richardson and Zhao 2009). A circular failure model was not considered in this study since rotational failure models overestimate the stability of slope when compared to translational block failure models (Mitchell et al. 1990).

Because of expected disparity between hydraulic conductivity of the cover materials and MSW, leachate may accumulate on top of the MSW layer (Jain et al. 2006, Johnson et al. 1998). At such locations, positive pore water pressure (PWP) may build, decreasing the normal stress on top of the bottom of the spot and thus decreasing the shear strength of the saturated material. This phenomenon may have significant effect on slope stability (Vafaeian et al. 2005). In this study a positive PWP value was assigned at several locations at the bottom of the cover layer to simulate perched leachate. Figure 2 shows an output example of SLOPE/W where PWP increase occurred due to perched leachate.

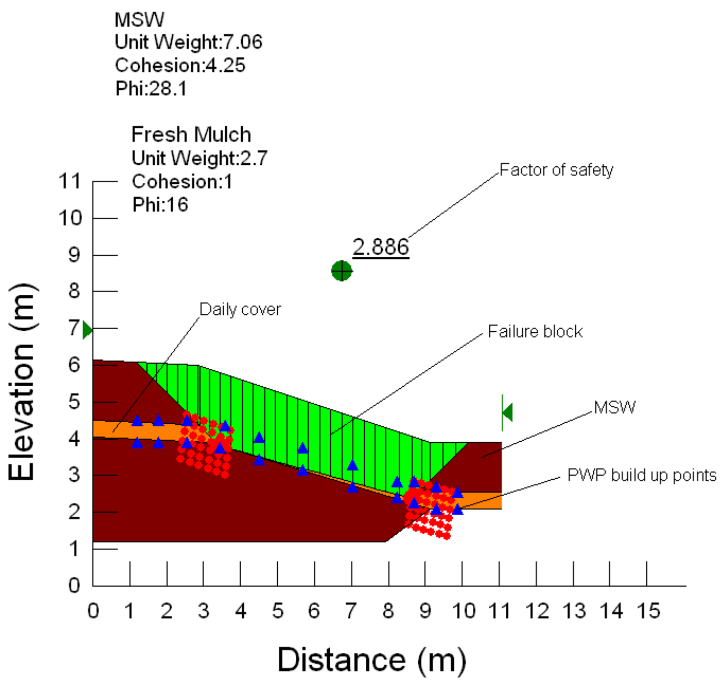


Figure 2. Slope Stability Analysis Using Slope/W.

Results and Discussion

Mulch Characteristics

To assess the impact of location or season on the properties of fresh mulch in Florida, the physical and engineering characteristics of the cover materials collected at five SWMFs were compared using the Analysis of Means (ANOM) statistical procedure at a confidence interval of 0.05. There were no statistically significant differences among fresh mulch samples. Average values of physical properties for fresh mulch samples were then compared across seasons using the ANOM statistical procedure at a confidence interval of 0.05. Seasonal change also had no statistically significant effect on physical and engineering properties of mulch. Therefore, average values of fresh mulch properties were used for comparison to properties of mulch/soil mixtures and soil. The statistical 1-tail t-test was used for comparisons between Fresh Mulch and other cover materials, at a confidence interval of 0.05. P-values above 0.05 suggest no statistical difference between the means of the two compared samples. All samples had properties that were statistically different than those of Fresh Mulch except for the friction angles of 1Y-Mulch and Fresh Mix; which had P-values greater than 0.05.

Table 2 provides the properties of the cover materials analyzed in this study. Bulk unit weight is generally used to measure the degree of compaction and volume reduction possible. The 1Y-Mulch had 18% higher optimum bulk unit weight than Fresh Mulch due to finer particle size distribution. Fresh Mulch had the lowest bulk unit weight of 2.7 kN/m^3 while the 3Y-Mix had the highest (9.4 kN/m^3) due to the added weight of soil. Mulch undergoes biological degradation which alters individual particle shape to become less angular over time. The reduction in particle size and angularity permits particles to pack tighter and thus achieve higher bulk unit weights. Over time, the mulched yard waste is composted; compost typically has a soil-like texture and particle size distribution with a unit weight in the range of 1.8-7.4 kN/m^3 (Peter and Brian 2001). The 3Y-Mix compacted more than compost but not as much as soil as suggested by bulk unit weight, mainly because of the remaining recalcitrant wood pieces that prevented more effective packing.

Table 2. Physical Properties of Cover Material Samples.

Cover Material Sample	**Friction Angle, Degrees**	**Porosity, %**	**Specific Gravity**	**Typical Hydraulic Conductivity, cm/sec**	**Dry optimum Unit Weight**, kN/m^3**
Fresh Mulch*	16	71	0.7	0.12	2.7
1Y- Mulch	16	65	0.8	0.09	3.2
Fresh Mix	15	61	1.5	0.05	5.6
1Y- Mix	12	56	1.6	0.04	6.7
3Y-Mix	11	49	1.9	0.01	9.4
Soil	10	42	2.2	0.003	12

*Average of 20 samples. All other values represent average of duplicate analysis.

**Values at optimum compaction.

Table 3 summarizes the results of the sieve analysis showing the attributes of particle size (D_{10}, D_{30}, and D_{60}) that were obtained from the particle size distribution curve and the USCS soil groups assigned based on the calculated C_u and C_c. Sieve analysis results showed that aged samples had finer particle size distribution than fresh samples due to biological degradation. More than 40% of the particles of the fresh mulch samples were larger than 1 cm, while 1Y-Mulch had 30% of particles larger than 1 cm.

More than 90%, by weight, of mulch had particles > 1 cm. these particles were angular heterogeneous wood pieces that provided higher degree of particle interaction. The relatively coarse size and irregular shape of particles in mulch was responsible for its higher porosity compared to soil and mulch/soil mixture. This property contributed to the higher hydraulic conductivity of compacted mulch samples which was one and nearly two orders of magnitude greater than that of mulch/soil mixtures and soil, respectively.

Both Fresh Mulch and 1Y-Mulch had values of C_u above 4 and values for C_c between 1 and 3 indicating a well-graded material. Fresh Mix had a value of C_u above 6 and a C_c between 1 and 3 indicating a well-graded material. However, as the mixture ages and degrades it becomes more uniform and has values of C_c below 1 indicating a poorly-graded material. Figure 3 provides particle size distribution for all samples and shows that particle size distributions became soil-like as particles degraded over time and samples became finer and more homogeneous. Mixtures of mulch and soil had lower friction angles (Table 2) than mulch alone due to a finer particle distribution (Table 3, Figure 3) that decreased particle interlocking.

Table 3. Particle Size Attributes of Cover Material.

Cover Material Sample	D_{10}, mm	D_{30}, mm	D_{60}, mm	C_u	C_c	Unified Soil Classification System, (ASTM 2487-10)
Fresh Mulch	3.1	6.9	13	4.2	1.2	well-graded gravel
1Y-Mulch	0.5	1.7	6.1	12.7	1.0	well-graded sand
Fresh Mix	0.2	1.0	4.9	25.8	1.1	well-graded sand
1Y-Mix	0.2	0.5	3.0	18.8	0.5	poorly-graded sand
3Y-Mix	0.10	0.2	1.1	11.0	0.5	poorly-graded sand
Soil	0.1	0.1	0.9	11.3	0.3	poorly-graded sand

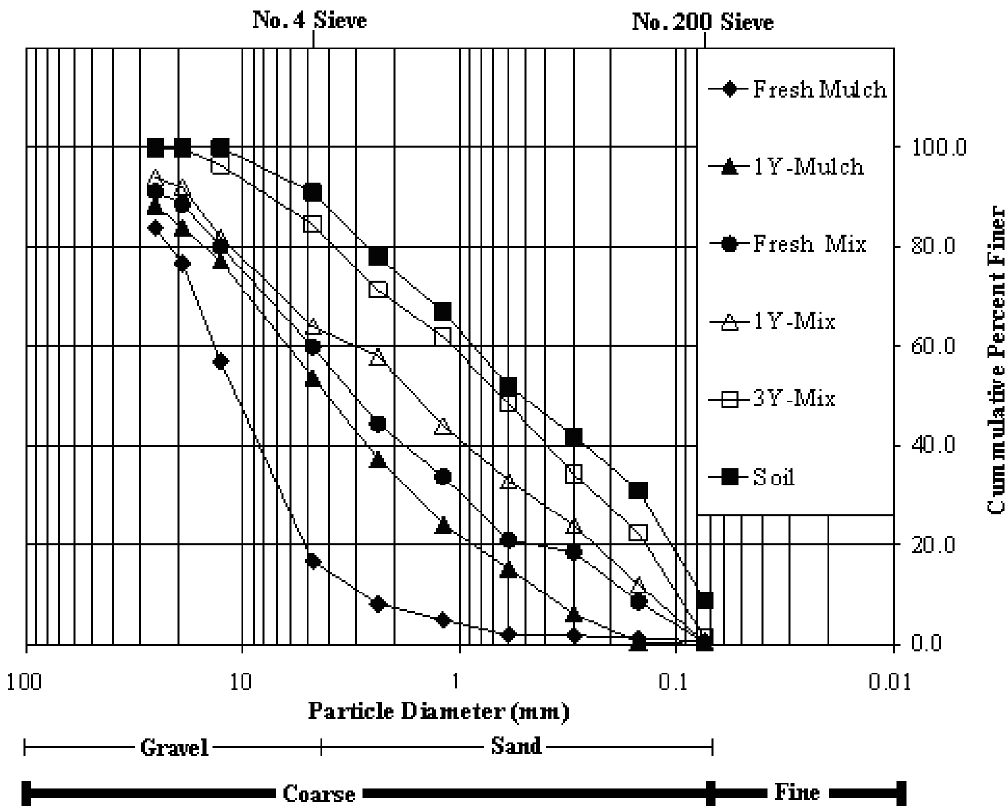


Figure 3. Particle Size Distributions for Cover Material.

Volume Reduction

Figure 4 shows the decrease in void ratio with increasing vertical stress for tested specimens. Void ratio remained constant for all samples at stresses below 1 kPa. Beyond 1-10 kPa, the plot slope sharply increased; such behavior is typical for soil consolidation tests (Bowles 1984). The flat part of the curve is termed the “initial branch”, while the sharp increase in slope is termed the “end branch”. Among tested samples, Fresh Mulch had the steepest end branch; this implies the sensitivity of mulch volume to vertical stress as compared to the rest of the tested material. Reduction in void ratio and consequential reduced volume could provide valuable landfill airspace savings. Compactors are expected to apply stresses on cover layers in the range of 60-

100 kPa (TC400 Product Bulletin), and MSW landfilled to depths of 30 m is calculated to create an overburden up to 200 kPa (Figure 4). At these typical landfill loadings, Fresh Mulch is expected to provide the highest volume reduction of all tested cover material. From Figure 4, Fresh Mulch could compact to as little as 46% of its original volume, while Mix and Soil samples could compact to 69% and 84% of their original volumes, respectively.

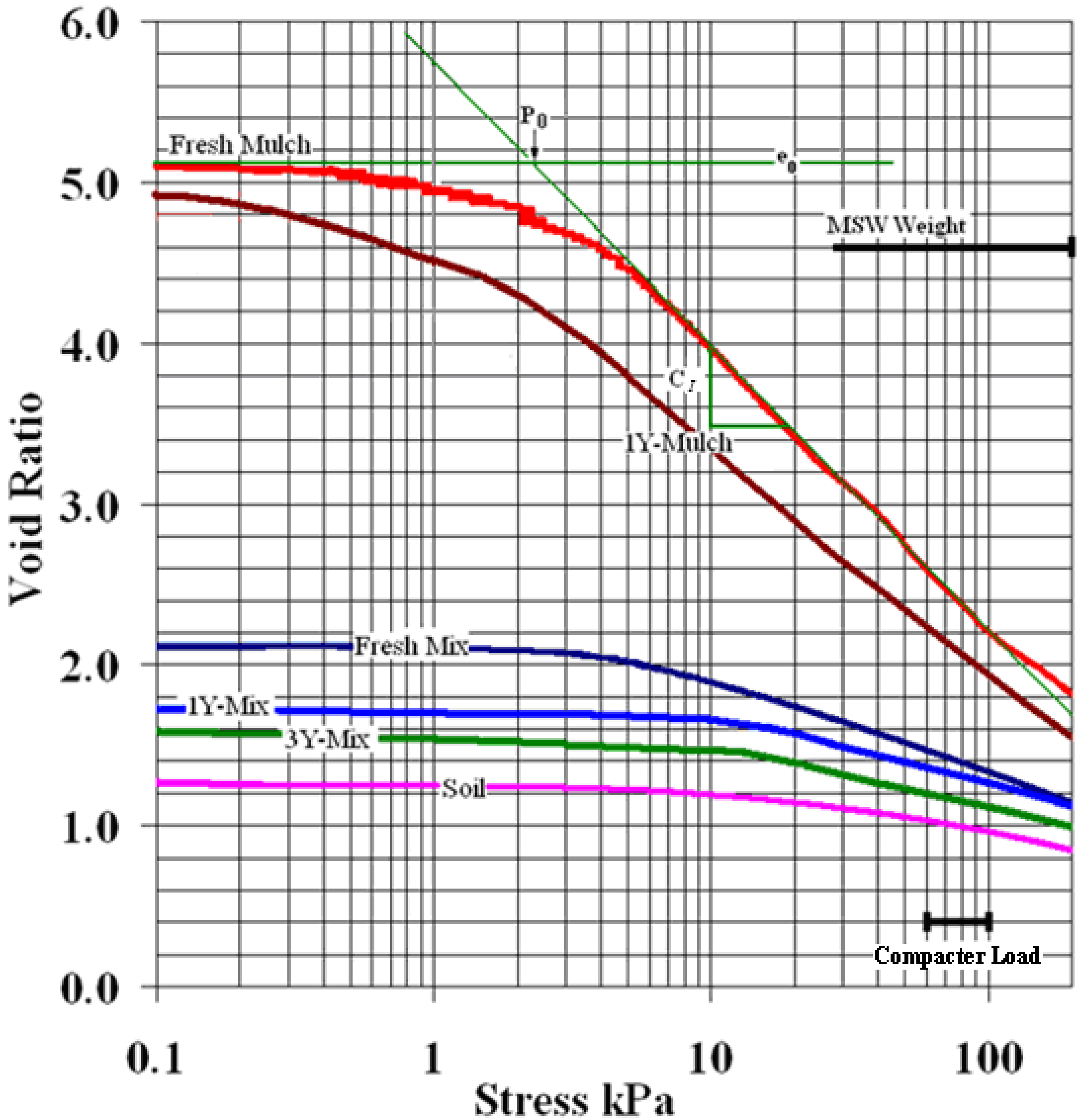


Figure 4. Axial Compression Test Curves for Soil, Mulch, and Mulch/Soil Mixtures.

The volume reduction provided by compaction of covers of a "typical" landfill using 15-cm daily covers and 2-m intermediate cover was calculated. Volume reduction of MSW was excluded from calculations to investigate the reduction of volume of cover material alone. The landfill was

30 m high with a footprint of 300 m x 300 m. The four sides of the landfill have slopes of 1:4, resulting in a 30 m x 30 m top flat area.

Table 4 presents the modeled landfill information. Volume reduction was calculated by dividing the landfill into *N* cover elements (each 15 cm x 15 cm x 15 cm). A minimum load of 100 kPa due to compaction weight was applied at each element. Each element, related to its position in the landfill, was additionally loaded with overburden stress up to 200 kPa, depending on the weight of MSW. This analysis only accounts for the reduction in volume of cover due immediate response to loading; while, in fact, time-dependant mechanical creep and biological decomposition of waste also contribute to landfill volume reduction (Marques et al. 2003). Therefore, only Fresh Mulch, Soil, and Fresh Mix were analyzed for volume reduction. Change in void ratio as a function of vertical stress was calculated for each element. The volume reduction for each element was then calculated, and a summation of all the values presented the total volume reduction of cover.

Table 4. Modeled Landfill Information for Volume Reduction Calculation.

Landfill Volume, m^3	1,404,000
Height, m	30
Landfill Footprint, m^2	90,000
Top Area, m^2	3,600
Side Slopes (Vertical : Horizontal)	1:4
Daily Cover Thickness, cm	15
Intermediate Cover Thickness, cm	60
Compactor Stress, kPa	100
Dry MSW Unit Weight, kN/m^3	7.0
Vertical Spacing Between Daily Cover Layers, m	2
Vertical Spacing Between Intermediate Cover Layers, m	10
Total Initial Cover Volume, m^3	153,000

Linear approximation of void ratio curves was carried out to enable calculation of the difference in void ratio at each stress point generated at different overburden depths in the landfill (Figure 4). Table 5 provides the cover material characteristics used to calculate the reduction in volume of each element. P_0 and C_I are characteristics of the end branches of void ratio curves and are determined from Figure 4. The initial effective overburden pressure (P_0) is the approximation of the initial load pressure that the sample was under, while the compression index (I_x) is the slope of the end branch.

Table 5. Cover Material Data for Volume Reduction Calculations.

	Mulch	Mix	Soil
Initial Void Ratio (e_0)	5.1	2.1	1.2
Mass of Cover Material Element, kg	0.3	1.1	2.3
Initial Effective Overburden Pressure (P_0), kPa	2.2	3.9	9.1
Compression Index (C_I)	1.8	0.5	0.2
Specific Gravity (G_S)	0.7	1.5	2.2

Difference in void ratio of each element was calculated as a result of vertical stress using Equation 3.9. Note that all stresses exceeded P_0.

$$\Delta e_n = C_I \log \frac{\sigma_n}{P_0} \tag{3.9}$$

Where,

Δe_n = Difference in void ratio of element n, unitless; C_I = Compression index of cover material;

P_0 = Initial effective overburden pressure, kPa; σ_n = Stress on top of element n, kPa.

Reduction in volume of n^{th} element was calculated using Equations 3.10 and 3.11.

$$\Delta Vv_n = Vs \times \Delta e_n \tag{3.10}$$

$$V_S = \frac{W_S}{G_S \times \gamma_w} \tag{3.11}$$

ΔVv_n = Reduction in void volume of element n under stress σ_n, m^3; V_S = Volume of solids in element, m^3; W_S = Weight of cover material in element, kN; G_S = Specific gravity of cover material, unitless; γ_w = Unit weight of water at 25 c^0, kN/m^3

Equations 3.12 and 3.13 were used to calculate the total percentage reduction in the original volume of the landfill.

$$\Delta V_N = \sum_{n=1}^{N} \Delta Vv_n \tag{3.12}$$

$$\text{Percent reduction in landfill volume} = \frac{\Delta V_N}{V_T} \times 100\% \tag{3.13}$$

Where,

ΔV_N = Total reduction in cover volume, m^3; V_T = Landfill original total volume, m^3

Table 6 provides the volume reduction modeling results. Soil covers provided the least volume reduction while use of mulch covers resulted in the highest volume reduction. Volume reduction of Mulch cover is a conservative estimate because additional volume reduction with time is expected due to secondary settlement (biological degradation and mechanical creep) and also because cover material was assumed to be placed on horizontal waste surfaces only.

Table 6. Volume Reduction Results for model landfill.

Cover Material	Total Volume Reduction, %	Cover Volume Reduction, %
Mulch	5	49
Mix	3	21
Soil	1	8

Slope Stability Modeling

Table 7 provides the slope stability modeling results for cover materials tested. All cover material had FS greater than 1.5 against tested failure. Higher shear strength, milder slopes, thinner covers, and lower unit weight resulted in greater FS. Fresh Mulch had the highest FS against both linear and block failure. Higher friction angle of Fresh Mulch increased the resistance to failure, and the lower unit weight of fresh mulch, compared to aged mulch, also reduced the slipping driving force in the linear and block failure model.

Fresh Mulch stability analyses show that replacing soil covers with mulch covers will actually increase the stability of the slope. Since shear strength of samples was directly related to their age, the stability decreased for samples that had experienced longer degradation due to a finer particle size distribution and decreased shear strength of cover material. Mulch cover stability on landfill slopes should not be considered without the influence of time on its strength properties. Extended degradation will eventually transform mulch into a mixture of soil-like material and pieces of wood, and while soil had the lowest FS against both linear and block failure; however FS was never below 1.5.

Pore water pressure build up reduced the FS and had a greater effect on thicker covers since more water can be stored and higher pressure can be achieved. Positive pore water pressure decreased the normal stress applied on the sliding surface, and consequently the shear strength of the saturated material, leading to a lower FS; however FS remained above 1.5.

Table 7. Factors of Safety Results for Exposed and Buried Covers on Slopes.

Cover Material	Cover Thickness, cm	Exposed (Linear failure)		Buried Cover: Block failure		Buried Cover: Block failure/Pore Water Pressure	
		Slope 1:3	Slope 1:4	Slope 1:3	Slope 1:4	Slope 1:3	Slope 1:4
Fresh Mulch	15	4.8	5.7	3.3	4.0	3.3	3.9
	30	4.1	5.2	3.3	3.9	3.1	3.7
	45	3.6	4.5	3.2	3.8	2.9	3.5
1Y-Mulch	15	4.8	5.7	3.3	4.0	3.3	4.0
	30	4.1	5.2	3.3	3.9	3.1	3.8
	45	3.6	4.5	3.2	3.9	2.9	3.5
Fresh Mix	15	4.7	5.6	3.2	3.9	3.2	3.9
	30	4.0	5.1	3.1	3.7	2.9	3.5
	45	3.5	4.4	2.9	3.5	2.7	3.2
1Y-Mixture	15	4.5	5.4	3.0	3.6	3.0	3.6
	30	3.8	4.9	2.7	3.3	2.7	3.2
	45	3.3	4.2	2.4	2.9	2.2	2.6
3Y-Mix	15	4.4	5.3	2.9	3.5	2.9	3.5
	30	3.7	4.8	2.6	3.1	2.5	3.0
	45	3.2	4.1	2.2	2.7	2.1	2.5
Soil	15	4.1	5.0	2.6	3.1	2.6	3.1
	30	3.4	4.5	2.3	2.8	2.3	2.7
	45	2.9	3.8	2.1	2.5	1.9	2.3

Conclusions

The angularity and size of mulch particles result in the high porosity that characterized the behavior of fresh mulch as a landfill cover, i.e., relatively high hydraulic conductivity, high shear strength, and low dry bulk unit weight. Therefore, mulch covers are expected to act poorly in controlling infiltration, generating greater amounts of leachate in landfills than soil covers. The difference in hydraulic conductivities of mulch and MSW may create perched liquid water on the less permeable layer of waste. This may lead to a build up of pore water pressure on top of the waste layer, decreasing the shear strength of the cover material. In this case, adhesion between the cover material and MSW declines; reducing the resistance against sliding. However, analysis of the stability of landfill slopes under pore water pressure consistently resulted in FS above 1.5.

The highly porous nature of mulch was also responsible for lower bulk unit weight of fresh mulch than that of soil. Use of mulch covers are expected to lead to recovery of as much as 5% of the original volume due to compaction under vertical stress. Additional volume reduction of mulch layers is expected to occur as a result of the biological degradation of the organic fractions. The significant volume reduction is considered beneficial in terms of landfill space savings, as opposed to conventional soil covers.

Mulch covers, whether exposed or buried, have more stability on landfill slopes than soil covers. However, it is expected that mulch will degrade and porosity, hydraulic conductivity, and shear strength will decline over time. Mixtures of soil and mulch may have optimum behavior as landfill daily cover; having lower hydraulic conductivity than mulch, and greater strength than soil.

Laboratory tests carried out in this study suggest that mulch covers could successfully function as alternative daily or intermediate cover with respect to the geotechnical behavior. However, landfill gas control by the cover material; a main function of daily and intermediate covers, was not explored in this study. Therefore, a complete assessment of mulch cover requires testing and monitoring in the field.

References

Abramson, L.W., Lee, T.S., Sharma, S., Boyce G.M. (2002). "Slope stability and stabilization methods". John Wiley and Sons 2002.

Allen, M.R., Braithwaite, A., Hills, C.C. (1997). "Trace organic compounds in landfill gas at Seven U.K. waste disposal sites". Environmental Science and Technology. 31:1054–1061.

Barlaz, M.A., Green, R.B., Chanton, J.P., Goldsmith, C.D., Hater, G.R. (2004). "Evaluation of a biologically active cover for mitigation of landfill gas emissions". Environmental science and technology. 2004, 38, 4891-4899.

Benson, C., Daniel, D., Boutwell, G. (1999), Field Performance of Compacted Clay Liners, J. of Geotech. and Geoenvironmental Eng., ASCE, 125(5), 390-403.

Benson, C.H., Majdi, A.O. (1993). “Hydraulic and Mechanical Characteristics of a Compacted Municipal Solid Waste Compost”. Waste Management and Research. 11(2):127-142.

Blight, G.E. (2006). “A survey of lethal failures in municipal solid waste dumps and landfills”. 5th International Congress on Environmental Geotechnics, Thomas Telford, London, 13-42.

Börjesson, G., Chanton, J., Svensson, B.H. (2001). “Methane oxidation in two Swedish landfill covers measured with carbon-13 to carbon-12 isotope ratios”. Journal of Environmental Quality, 30, 369–376.

Buggeln, R., Rynk R. (2002). “Self-heating in yard trimmings: conditions leading to spontaneous combustion”. Compost science and utilization, vol. 10, no. 2, p162-182, 2002.

Cassel, D.K., Nielsen, D.R. (1986). “Methods of Soil Analysis: Part 1. Physical and Mineralogical Methods”. 2nd edition American Society of Agronomy, Madison, WI, pp. 901-926.

Chanton, J., Liptay, K. (2000). “Seasonal variation in methane oxidation in a landfill cover soil as determined by an in situ stable isotope technique”. Global Biogeochemical Cycles, 14, 51–60.

Code of Federal Regulations - Title 40: Protection of Environment. December 2005

Darlington, W., “Compost--A Guide for Evaluating and Using Compost Materials as Soil Amendments” Soil and Plant Laboratories, Inc.

Evanylo, G., McGuinn, R. (2000). “Agricultural management practices and soil quality: Measuring, assessing, and comparing laboratory and field test kit indicators of soil quality attributes”. VA Coop. Ext. Publ. No. 452-400.

Florida Organics Recyclers Association (1996). “Recycling Yard Trash: Best Management Practices Manual for Florida”.

Hazen, A. (1911). “Discussion: dams on sand foundations.” Transactions of the American Society of Civil Engineers 73:199.

Haughey, R. D. (2004). “Landfill alternative daily cover: conserving airspace and reducing landfill operating cost”. Journal of waste management resource 19, 89-95.

Humer, M., Lechner P. (1999). “CH4 oxidation in compost cover layers on Landfills. Proceeding of Seventh International Waste Management and Landfill Symposium, Cagliari, Italy. 1999”.

Humer, M., Gebert, J., Hilger, H. (2004). “Biotic Systems to mitigate landfill methane emissions“. Waste Management and Research 26:33-46.

Hurst, C., Longhurst, P., Pollard, S., Smith, R., Jefferson, B., Gronow, J. (2005). “Assessment of municipal waste compost as a daily cover material for odour control at landfill sites”. Environmental Pollution, Vol 135, p (171-177).

Jain, P., Powell, J., Townsend T., Reinhart D.R. (2006). “Estimating the hydraulic conductivity of landfill municipal solid waste using the borehole permeameter test”. Environmental Engineering, June 2006.

James, L. H. (1960). “Changes in Putting Green Construction Concepts”.

Johnson, A. C., Richner, G. A., Vitvar, T., Schittli, N., Eberhard, M. (1998). “Hydrological and geochemical factors affecting leachate composition in municipal solid waste incinerator bottom ash: Part I: The hydrology of Landfill Lostorf, Switzerland”. Journal of Contaminant Hydrology (33) 361-376.

Jugnia, L., Cabral, A., Greer, C. (2008). “Biotic methane oxidation with an instrumented experimental landfill cover”. Ecological Engineering 33 (2008) 102-109.

Kaufman, S. M., Themelis, N. J. (2009). “Using a direct method to characterize and measure flows of municipal solid waste in the United States”. Journal of the air and waste management association. 59, 1386-1390.

Khire, M.V., Benson, C.H., Bosscher, P.J. (1997). “Water Balance Modeling of Earthen Final Covers”. Geotechnical and Geoenvironmental engineering August 1997.

Koerner, R. M., Soong, T. Y. (2005). “Analysis and design of veneer cover soils”. Geosynthetics International. 12(1):28-49.

Koerner, R. M., Hwu, B. L. (1991). “Stability and tension considerations regarding cover soils on geomembrane lined slopes”. Journal of Geotextiles and Geomembranes, 10, No. 4, 335-355.

Liptay, K., Chanton, J., Czepiel, P., Mosher, B. (1998) “Use of stable isotopes to determine methane oxidation in landfill cover soils”. Journal of Geophysical Research, 103, 8243–8250.

Marques, A., Filz, G., Vilar, O. (2003). “Composite Compressibility Model for Municipal Solid Waste”. Journal of Geotechnical and Geoenvironmental Engineering (2003)129:4(372).

McFarlane, I.C. (1969). “Muskeg Engineering Handbook” University of Toronto Press 1969, pp 31-52.

Milind, V. K., Craig H. B., Peter J. B. (1997). “Water Balance Modeling of Earthen Final Covers” journal of geotechnical and geoenvironmental engineering. August 1997 p. 744.

Mitchell, J. K., Seed, R. B., Seed, H. B. (1990). "Kettleman Hills waste landfill slope failure I: Liner system properties". Journal of Geotechnical Engineering, 116~4!, 647–668.

Mitchell, J.K. (1976). "Fundamentals of soil behavior" John Wiley and Sons Inc. New York, NY.

Muntoni, A., Cossu, R. (1997). "Influence of compost covers on landfill gas surface emissions." Proceedings of Sixth International Landfill Symposium, Sardinia, 1997. 115–125.

Orquin, R., Abad, M., Noguera, P., Pulchades, R. , Maquieira, A., Noguera, V., Iglesia, F. (2001). "Composting of Mediterranean seagrass and seaweed residues with yard waste for horticultural purposes" Acta Horticulturae, 549: 29-35.

Pacific Region Pocket Handbook, USDA - SCS - E–15 and Water Management Note-Estimating soil moisture by feel and appearance, High Plains Underground Water Conservation District No. 1.

Paquet, J.M., Caron, J., Banton, O. (1993). "In situ determination of the water desorption characteristics of peat substrates". Canadian Journal of Soil Science. 73:329–339.

Peter, J.S, Brian, A.K. (2001). "Compost Utilization in Horticultural Cropping System". CRC Press 2001.

Performance and Design for Compost Erosion Control and Compost Storm Water Blankets, "Proceedings of the EC-08, Orlando FL: International Erosion Control Association Annual Conference".

Qian, X., Koerner, R.M., Gary, D.H. (2002). "Geotechnical Aspects of Landfill Design and Construction", Prentice Hall.

Reinhart, D., Chopra, M., Sreedharan, A., Koodthathinkal, B., Townsend, T., (2003). "Design and Operational Issues Related to the Co-Disposal of Sludges and Biosolids in Class I Landfills". Report to the Florida Center for Solid and Hazardous Waste Management.

Richardson, G.N., Zhao A. (2009). "Geosynthetic Fundamentals in Landfill Design". Proc. of Int. Symp. on Geoenvironmental Eng., ISGE2009 September 8-10, 2009, Hangzhou, China.

Scheutz, C., Bogner, J., Chanton, J., Blake, D., Morcet, M., Kjeldsen, P. (2003). "Field measurement of non-methane organic compound emissions from landfill cover soils." Environmental Science and Technology. 2003, 37, 5150-5158.

Soil Conservation Service, Urban Hydrology for Small Watersheds, Technical Release 55, U. S. Department of Agriculture, Washington, D. C., 1986.

Shafer, A. L., Hargrove, J.Q., Harris, J.M. (2000). "Stability Analysis for Bioreactor Landfill Operations".

Shepherd, R.G. (1989) "Correlations with permeability and grain size." Ground Water 27(5):633–638.

Stephens, 2007. "Innovations-Case studies: Organic option" http://www.ciwmb.ca.gov/LGlibrary/Innovations/Organics/Trimmings.htm (Last accessed June 2010).

United States Environmental Protection Agency/Office of Solid Waste (2008). "Municipal Solid Waste in the United States: 2008 Facts and Figures".

United States Environmental Protection Agency (EPA 2007). "Municipal solid waste generation, recycling, and disposal in the United States: Facts and figures for 2006".

Unified Soil Classification System, ASTM D2487-10 "Standard Practice for Classification of Soils for Engineering Purposes".

Vafaeian, M., Mansoorzadeh, M., Mirmohammad, M. (2005). "Influential factors in evaluating the construction pore pressure in earth dams by using UDAM program". Geotechnical and Geological Engineering (2005) 23: 87–103.

Vesilind, P.A., Worrell, W., Reinhart, D.R. (2002). "Solid Waste Engineering". Brooks/Cole, Pacific Grove, Ca, USA.

CHAPTER 4: FIELD ASSESSMENT OF VEGETATIVE MULCH AS INTERMEDIATE LANDFILL COVER

Introduction

According to Subtitle D of the Resource Conservation and Recovery Act (RCRA) codified in the Code of Federal Regulation (CFR) 258.21Section (a); landfill owners and operators are required to cover the active face of the landfill at the end of every day (or at more frequent intervals if necessary) to control disease vectors, fires, odors, blowing litter, moisture infiltration and scavenging. An intermediate cover is placed on the top areas of a landfill that will not be used for a long period of time (90 days according to State of Florida regulations). Infiltration can be controlled through the compaction of the material used as landfill intermediate cover (usually 60 cm of compacted earth) by minimizing both the hydraulic conductivity and the pore size (Jang et al., 2002). Intermediate landfill covers must have sufficient shear strength to resist sliding on the slope and tensile capacity to prevent cracking during local subsidence (Benson and Othman, 1993).

Section (b) of CFR 258.21 allows the use of an alternative material for alternative cover if the owner or operator demonstrates that the alternative material and its thickness will function the same as a soil cover and will not present a threat to human health and the environment. Materials for alternative landfill covers investigated to date include paper mill sludge, fly ash, mulched wood material, tarps, foams, and shredder fluff (Bracci et al., 1995; Bradley et al., 2001; Carson, 1992l; Hancock et al., 1999; Shimaoka et al., 1997). Haughey (2001) classified alternative daily covers into three broad categories; blankets, sprays, and waste materials.

Geotechnical properties of vegetative mulch, soil, and soil/mulch mixture were determined previously (Chapter 3) and were used to model the stability of daily and intermediate covers on landfill slopes using linear and block failure models. Bulk unit weight was 2.7, 5.6, and 12 kN/m^3, specific gravity was 0.7, 1.5, and 2.2, porosity was 71, 61, and 42% (of total volume), saturated hydraulic conductivity was 0.12, 0.05, and 0.003 cm/sec, and internal friction angle was 16^0, 15^0, and 10^0 for fresh mulch, soil/fresh mulch mixture, and soil; respectively. Stability modeling produced safety factors higher than 1.5 (the threshold for slope failure) and failure of either mulch or soil/fresh mulch mixture covers on slopes was not anticipated. The behavior of mulch and soil mixtures was also investigated in comparison with mulch and soil covers.

It is anticipated that vegetative mulch could provide volatile organic compound (VOC) emissions control, provide cost savings over soil or compost covers, save space in landfills as it degrades over time, and result in carbon sequestration within the landfill related to recalcitrant organic fractions. However, mulch has never been evaluated in the field for use as cover material. This study investigates the use of vegetative mulch as landfill covers by assessing the behavior of mulch covers through field testing and hydrologic modeling.

Background

Landfill gas typically consists of up to 65% v/v CH_4 and 35% v/v CO_2, both of which are considered to be greenhouse gases contributing to global climate change (Allen et al., 1997). Landfills are ranked as the second largest methane source in the US (USEPA 2010). Biological oxidation of CH_4 occurring in landfill covers is considered a complementary approach to landfill gas collection system in minimizing landfill emissions (Barlaz et al., 2004; Berger et al., 2005; Abichou et al., 2006). The capacity of landfill covers to oxidize CH_4 emissions has a major influence on landfill fugitive emissions (Mosher et al. 1999). Although compost is frequently used as a landfill cover (Haughy 2001); the effectiveness of vegetative mulch and soil/mulch mixtures to control CH_4 emissions has not been assessed to date.

Kightley et al. (1995) found that amendment of soil with coarse sand enhanced CH_4 oxidation capacity by 26% compared with un-amended control soil. Berger et al. (2005) reported that 57–98% of CH_4 was oxidized within a simulated landfill cover; the maximum value was achieved by porous, coarse, sandy soil. Generally, topsoil with coarse texture provides a higher CH_4 oxidization rate than fine soils due to improved aeration capacity (Boeckx et al., 1997; Berger et al., 2005; Watzinger et al., 2005).

The effect of cover material texture on porosity not only determines the degree of aeration, but also determines the moisture storage capacity. Moisture content and degree of saturation are important factors controlling CH_4 emissions from landfills (Bogner et al., 1995; Boeckx and van Cleemput, 1996). The biological degradation process requires a moist environment; however, a soil with high moisture content reduces the CH_4 transport to the CH_4-oxidizing community. Also, under trapped-water circumstances, the soil becomes anaerobic preventing CH_4 oxidation (Jugnia et al. 2008).

Material and Methods

Site description

Five test plots were created within a 100-m^2 area at a Solid Waste Management Facility (SWMF) in Florida, in a disposal area where waste placement would not take place for at least two years. Plots were built on top of 10-year old municipal solid waste (MSW). Figure 5 shows the dimensions and the basic features of the test plots. Existing cover was removed and replaced with either mulch, on-site cover soil, or a 50% (v/v) mulch-soil mixture. Top slope was graded to 1:3 or 1:4 (v:h). Table 8 provides dimensions of each plot. The plots were constructed with shallow pans buried at the end of each slope to collect runoff, directed into the collectors by runoff diverters. Mulch and soil plots were monitored from November 2008 through June 2010, while the soil/mulch mix plot was monitored from August 2009 through June 2010. Table 9 provides the monitored parameters in this study along with the procedures used.

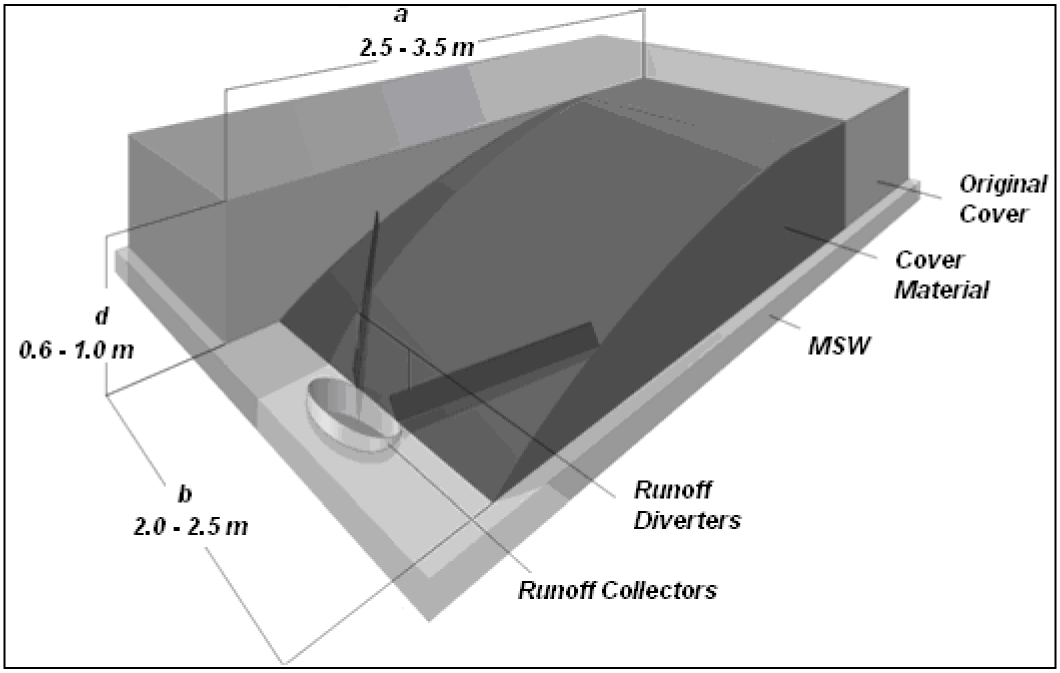


Figure 5. Schematic Drawing of Test Plots.

Table 8. Description of the Plots.

Plot	Cover Material	Slope (v:h)	Dimensions (a x b x d)*, m
S1	Soil	1:3	2.2 x 3.0 x 0.8
S2	Soil	1:4	2.3 x 2.9 x 1.0
M1	Mulch	1:3	2.5 x 2.5 x 0.6
M2	Mulch	1:4	2.0 x 2.5 x 0.8
SM	Soil/Mulch Mixture	1:3	2.0 x 2.5 x 0.9

*Refer to Figure 5

VOC Emissions Analysis

VOC flux measurements were obtained at each test plot on a weekly basis to measure the ability of cover material to control gas emissions. Flux readings were taken in duplicate over 15 and 60-cm cover depths to assess the effect of cover depth on VOC removal. To measure the loading flux, the existing cover material was temporarily removed to allow for flux chamber measurements directly from the waste. The mass flux of VOCs was measured using the dynamic flux chamber method, and concentration of VOCs in the exit gas from flux chamber was measured using a flame ionization detector (FID). Methane represents 99% of the VOC (Kreith, 1995); while 1% is saturated and unsaturated hydrocarbons, acidic hydrocarbons, organic alcohols, halogenated compounds, aromatic compounds and sulfur compounds (Keller, 1988). Hence, in this study, VOC concentration was used as a surrogate measure for methane.

Table 9. Set of Parameters Monitored for Each Plot.

Parameter	Standard Test	Frequency
VOC flux	Dynamic flux chamber [Kienbusch 1986]; VOC concentration inside the chamber was measured using the FID (User's Manual for MicroFID-2002).	Weekly
Runoff	Volume measurement of water in runoff collector	After each precipitation event
Precipitation	Depth measurement of water in rain gage	
Change in moisture content	Determination of water (moisture) content of cover material before and after precipitation events [ASTM D2216]	Before and after each precipitation event
Evaporation	Depth measurement of water in evaporation pan	
Cover Volume	Depth measurement of cover	Weekly

Water Balance

Plots were monitored before and after precipitation events to collect the data required for the water balance. Two rain gauges and two evaporation pans were used to provide duplicate measurements for precipitation depth and evaporation. Runoff depth was calculated by dividing volume of water in the runoff collector by the surface area of the plot. Water storage in cover material was calculated by measuring the moisture weight content of cover (ASTM 2216) and then converting that to volumetric moisture content. The difference in the volumetric moisture contents immediately after one precipitation event and before the next event was then multiplied by the average depth of cover to calculate the change in water storage depth in cover material.

Infiltration through covers occurring during a precipitation event was calculated using the water balance shown as Equation 4.1:

$$D_{Ip} = D_P - (D_R + \Delta M_C) \qquad (4.1)$$

Where,

D_{Ip} = Infiltration during precipitation, cm; D_P = Precipitation, cm; D_R = Runoff, cm; ΔM_C = Change in water storage of cover material, cm.

During a precipitation event evaporation was assumed to be zero and precipitation (D_P) was assumed to enter the runoff collector (D_R), infiltrate through the cover (D_I), or be stored within the cover material (ΔM_C). However, the stored water continued to evaporate, infiltrate, or runoff after the storm ceased, thus infiltration between precipitation events (D_{Is}) was calculated using Equation 4.2. Total amount of infiltration (D_I) was calculated using Equation 4.3.

$$D_{Is} = \Delta M_C - (D_E + D_R) \qquad (4.2)$$

Where,

D_{Is} = Infiltration of storage water between precipitation events, cm; D_E = Evaporation loss, cm.

$$D_I = D_{Ip} + D_{Is} \tag{4.3}$$

Where,

D_I = Total infiltration, cm.

Water Balance Modeling

The amount of leachate generated is primarily dependant on the landfill cover performance (Khire et al. 1997). To assess and compare the performance of mulch, soil and mix covers as hydraulic barriers for landfills, hydrologic modeling was conducted using the Hydrologic Evaluation of Landfill Performance (HELP) model. HELP is a quasi-two-dimensional, deterministic, water-routing model for determining landfill water balances. HELP versions, 1, 2, and 3 were developed by the U.S. Army Engineer Waterways Experiment Station, Vicksbury, M.S. for the USEPA Risk Reduction Engineering Laboratory, Cincinnati, OH, in response to needs of the Resource Conservation and Recovery Act and the Comprehensive Environmental Response, Compensation, and Liability Act (HELP Model: Volume I. User's Guide for Version 1. Draft Report, 1984).

The primary purpose of the model is to assist in the comparison of landfill design alternatives. HELP utilizes simplified scenarios to model the routing of water through soil layers and removal of water through overland flow and evapotranspiration. It also provides a list of saturated and unsaturated material properties for different types of materials. The software requires input data regarding the material including; porosity, saturated hydraulic conductivity, and runoff curve number (CN). Cover material characteristics for simulations were determined from field and laboratory tests (Chapter 3) and from literature. Precipitation and runoff data collected during each precipitation event were used to calculate CN using the empirical formulas developed in the SCS CN method (USDA 1985) to simulate the rainfall-runoff process (Equations 4..4 and 4.5). Precipitation and runoff values were used to solve Equation 4.4 for *S*, which was used to calculate *CN* in Equation 4.5 for each precipitation event. An average CN estimate was calculated for each cover material.

$$D_R = \frac{(D_P - 0.2S)^2}{(D_P + 0.8S)} \tag{4.4}$$

$$CN = \frac{1000}{S + 10} \tag{4.5}$$

Where,

S = Retention parameter; *CN* = Curve number.

Cover Volume Reduction

Changes in cover depth were monitored for each plot to calculate the reduction in volume. Volume reduction of landfill cover material could be due an immediate response to loading, or mechanical creep and biological decomposition of the material (Marques et al. 2003). Mulch, mulch/soil mixtures, and soil covers were found to lose 5, 3, and 1% of their original volume under typical normal stresses of MSW overburden and compactors weight experienced in landfills (Chapter 3). However, volume reduction measured in the field was related to biological degradation of the organic fraction of the cover material.

Results and Discussion

VOC Emissions Control Assessment

Table 10 provides VOC loadings into the plots and steady-state surface emissions over 15 and 60-cm cover thicknesses, along with the mass and percent removal of VOC. VOC emission rate from buried MSW is a parameter that can not be controlled in field testing of landfill covers. A number of researchers (Barry 2003, Borjesson et al. 2000, Caredellini 2003, Paladugu 1994, Rash 1992, Ishigaki et al. 2005, Bogner et al. 2000, and Walker 1991) have reported CH_4 flux rates from various landfills ranging from 0.365 to 6144 g/m^2-day.

Table 10. Steady-State VOC Flux Data.

	Loading, g/m^2-day (St. dev.)	Surface Emissions, g/m^2-day (St. dev.)		Average Removal, g/m^2-day		Average Removal, %	
		60cm	15cm	60cm	15cm	60cm	15cm
S1	0.31 (0.02)	0.22 (0.02)	0.24 (0.02)	0.08	0.07	27	23
S2	0.31 (0.02)	0.25 (0.01)	0.25 (0.01)	0.06	0.05	20	18
M1	10.4 (0.56)	6.17 (1.31)	7.13 (1.28)	4.24	3.10	41	30
M2	1.6 (0.26)	0.17 (0.17)	0.29 (0.19)	1.44	1.31	90	82
SM	1.3 (0.01)	1.00 (0.06)	1.08 (0.04)	0.28	0.19	22	15

In this study, a wide range of loadings was observed among the test plots. Mulch plots had gas flux loadings one order of magnitude higher than soil and mix plots. Because of the spatial proximity of the plots and the higher porosity of mulch compared to soil and soil/mulch mixtures; it is believed that mulch plots created preferential pathways for landfill gas emissions.

Figures 6 through 10 show the development of VOC removal with time. VOC flux measurements immediately after placing the covers showed that little to no oxidation of VOC gas was taking place. However, removal efficiency at all plots increased over time and steady-state conditions were observed after approximately seven months. Gradual increase of CH_4 removal is linked to the growth of methanotrophs. Methanotrophic counts in biocovers were studied by Ait-Benichou et al. 2009, where a slow development in methanotrophs numbers was exhibited. Increase in cover oxidation activity over 24 hours period of time was noticed in laboratory tests in previous studies (Kightley et al. 1995, De Visscher et al. 1999, and Visscher et al. 2001). Another factor that leads to changes in CH_4 removal is the competition with other soil microorganisms for finite supply of nutrients, fixed nitrogen, phosphate, and oxygen (Mancinelli 1995). However, methanotrophs are more tolerant to these limitations and thus eventually dominate (Clarholm 1984).

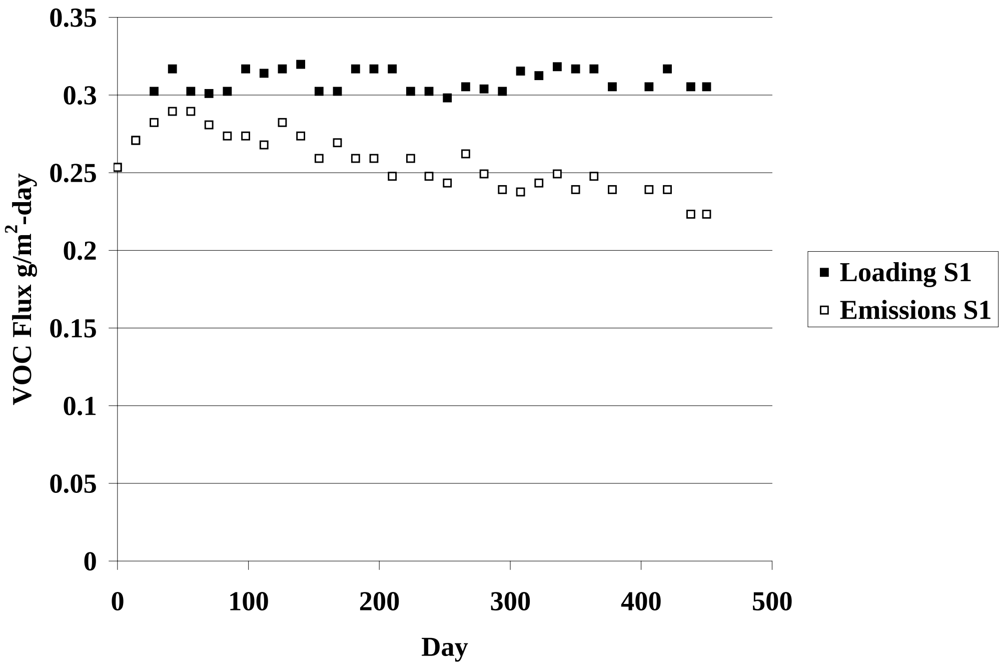


Figure 6. VOC Loading and Surface Emission Date-S1 Cover.

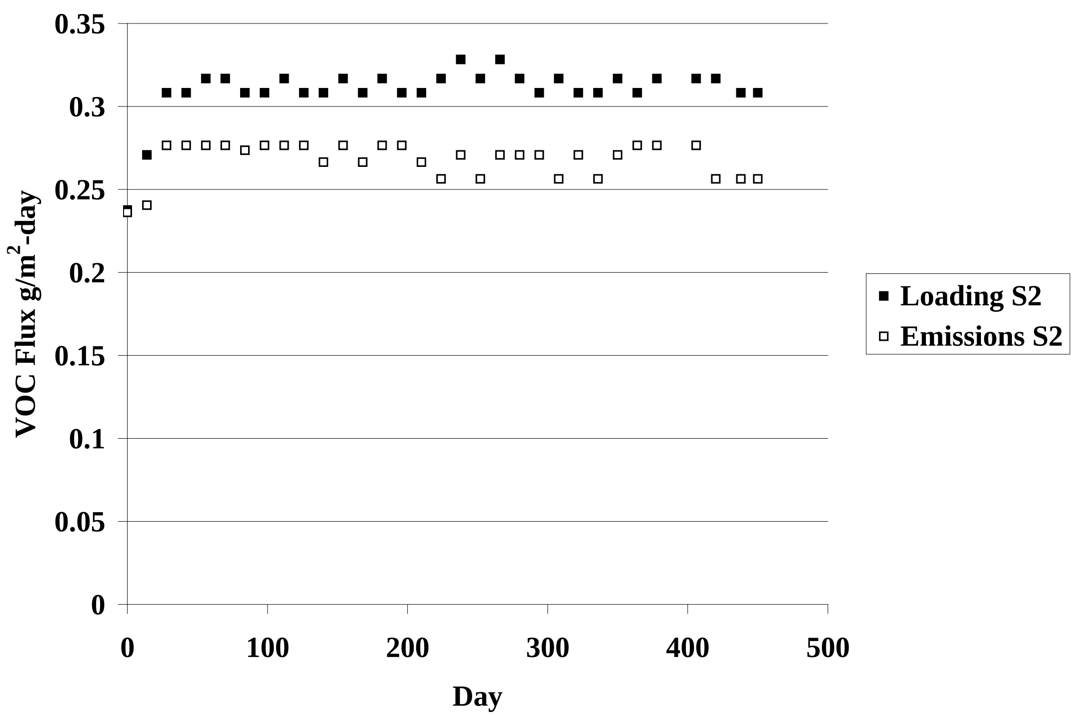


Figure 7. VOC Loading and Surface Emission Date-S2 Cover.

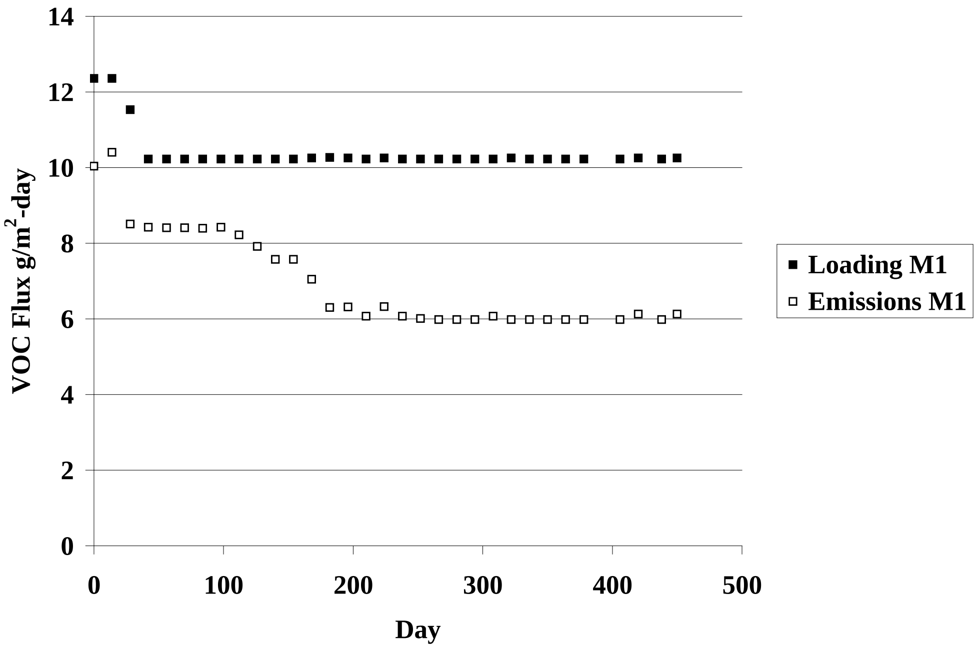


Figure 8. VOC Loading and Surface Emission Date-M1 Cover.

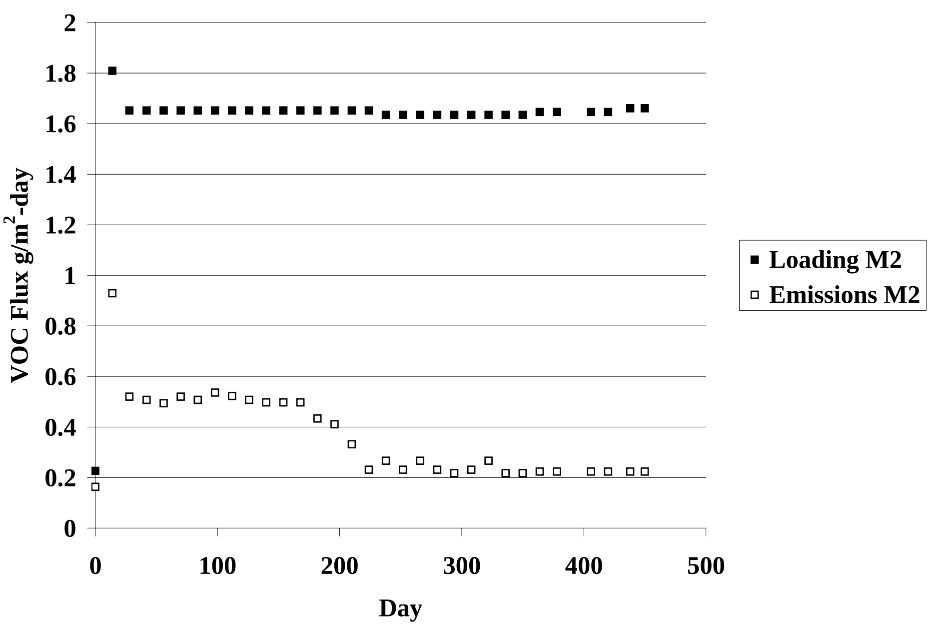


Figure 9. VOC Loading and Surface Emission Date-M2 Cover.

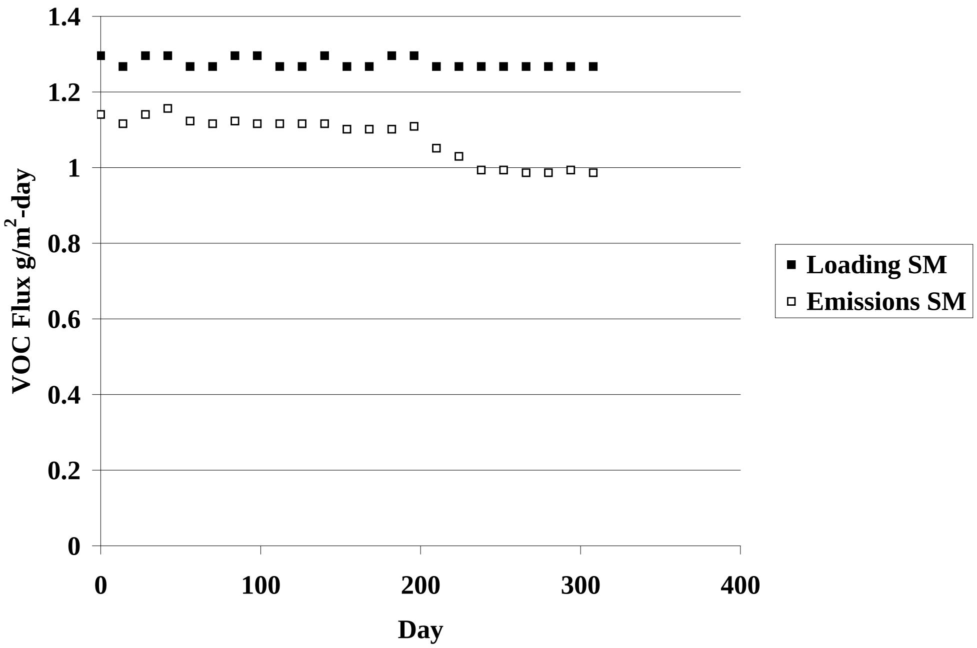


Figure 10. VOC Loading and Surface Emission Date-SM Cover.

Table 10 also presents removal rates for 15 and 60-cm cover thickness. Removal percentage through the 60-cm cover depth was always higher than that of the 15-cm depth. Clearly, a thicker cover, leading to a longer reaction path, increases retention time for CH_4 oxidation and consequently promotes higher removal efficiency (Abichou et al., 2006; Stern et al., 2007). VOC removal efficiency appeared to be correlated with VOC loading, perhaps due to increased methanotroph counts. Figure 11 shows the relationship between VOC removal and loading; Figure 12 provides the oxidation efficiency of the covers.

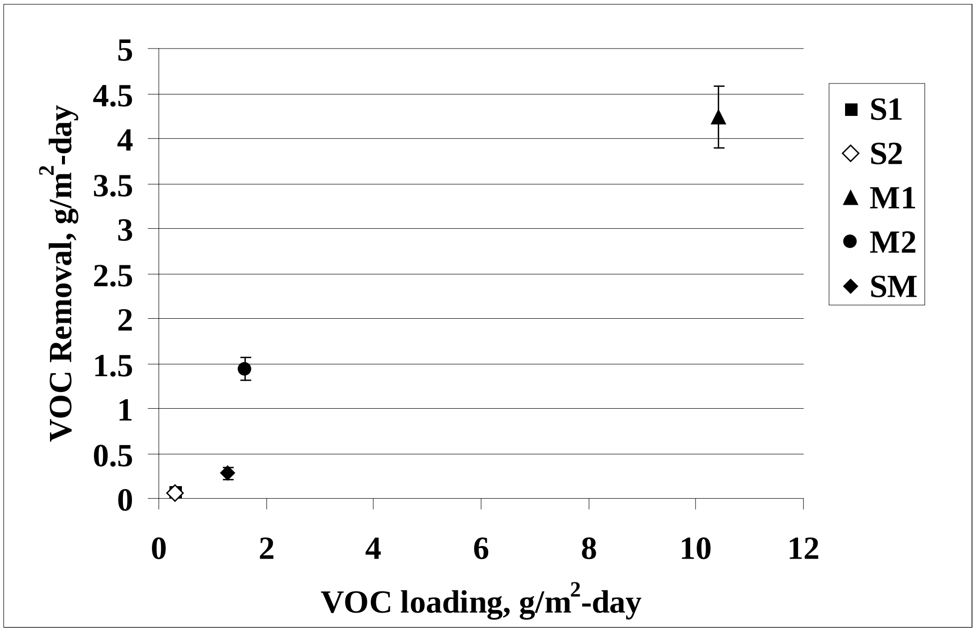


Figure 11. Steady-State VOC Removal (60-cm Cover) as Function of VOC Loading.

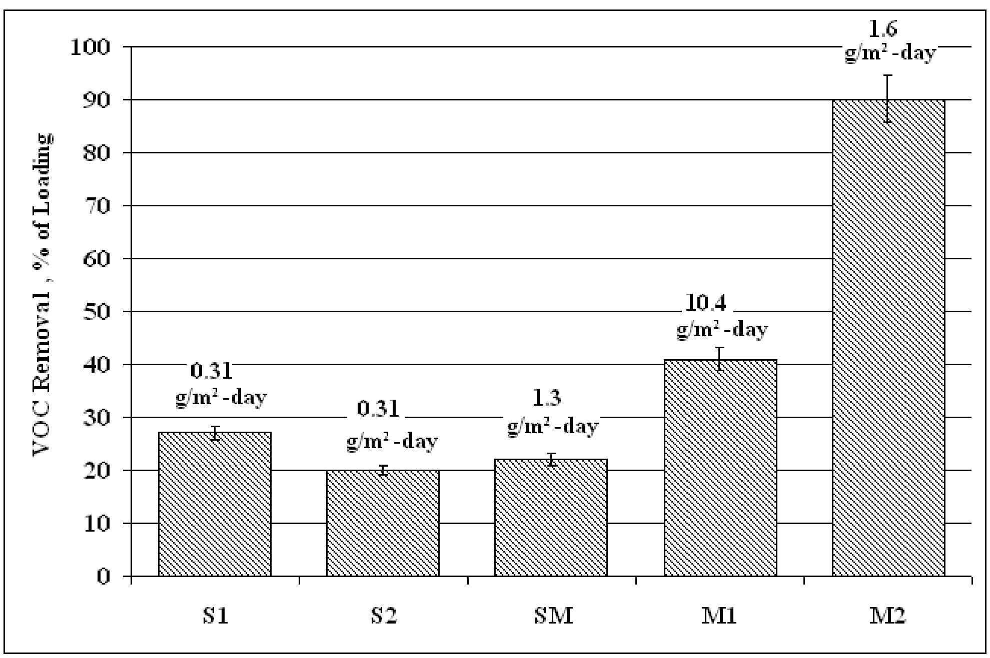


Figure 12. Steady-State VOC Percent Removal (60-cm Cover) as Function of VOC Loading.

Soil covers had removal efficiencies in the range of 20-27%. Soil covers have been shown to have removal efficiencies of approximately 39-54% at CH_4 loadings less than 10 g/m^2-day (Chanton et al. 2010), although the depth of cover was not specified in that study. Soil/mulch mix cover had similar removal efficiencies to soil covers (22%) despite higher loadings for the mix cover. Mulch covers achieved higher VOC removals than mix and soil covers presumably due to greater porosity of mulch (71%) than soil (42%) and mix (61%) covers. Biocovers with high porosity offer better environmental conditions for methanotrophs to grow than soil covers and thus improve CH_4 oxidation (Abichou et al., 2006; Stern et al., 2007). Amendment of landfill cover soils with organic materials can enhance soil capacity to hold water which may also promote oxidation (Stern et al., 2007; Huber-Humer, 2004; Huber-Humer et al., 2008).

Figure 12 shows lower VOC percent removal for mulch covers at higher VOC loadings, suggesting a non-linear behavior similar to Monod kinetics. Molins et al. (2008) used a Monod-type expression to model CH_4 oxidation while investigating the degradation and transport of gas in landfill soil covers. CH_4 oxidation in laboratory experiments was found to follow Monod kinetics; where kinetics were first order and zero order at low and high VOC concentrations, respectively. (Czepiel, et al. 1996, Czepiel et al., 1993, Whalen et al., 1990, Bender and Conrad 1993). In a previous study, soil covers have demonstrated linear removal with increasing CH_4 loading that eventually leveled off to a relatively flat value at higher CH_4 loadings (Chanton et al. 2010). However, there were insufficient VOC removal data points in our study to draw strong conclusion regarding the relationship between loading and removal of CH_4.

Cover Water Balance Results

Figure 13 provides the percentage of precipitation that infiltrated as a function of precipitation depth. Slope of plot covers did not affect infiltration. Covers had similar behavior at low precipitation (<0.015 m); producing almost no runoff. However, soil and mix plots generated more runoff compared to mulch plots at higher precipitation. Precipitation above 0.02 m produced standing water above soil covers due to total saturation of cover, while the relatively high hydraulic conductivity (0.1 cm/sec) of mulch prevented any ponding of water on top of mulch plots. Figure 14 provides runoff generation at each plot as a function of precipitation. Mulch plots generated almost no runoff even during precipitation as high as 0.08 m.

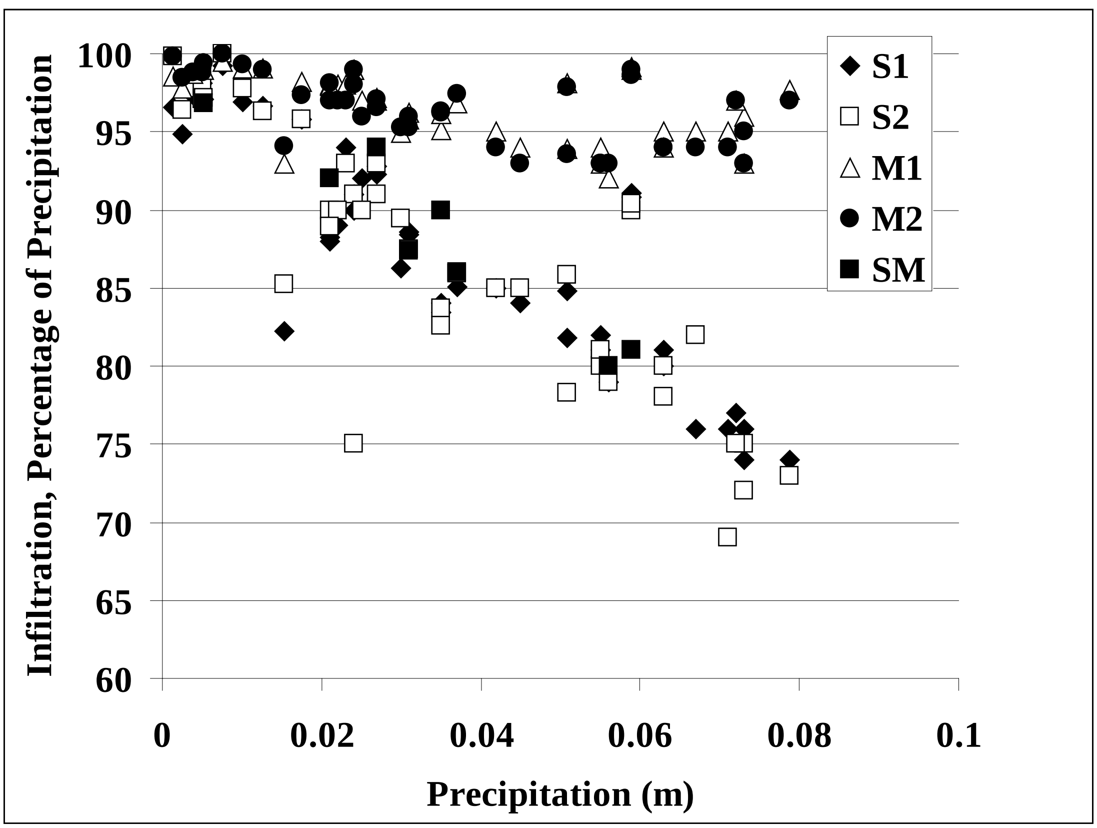


Figure 13. Infiltrating Behavior of Field Test Covers.

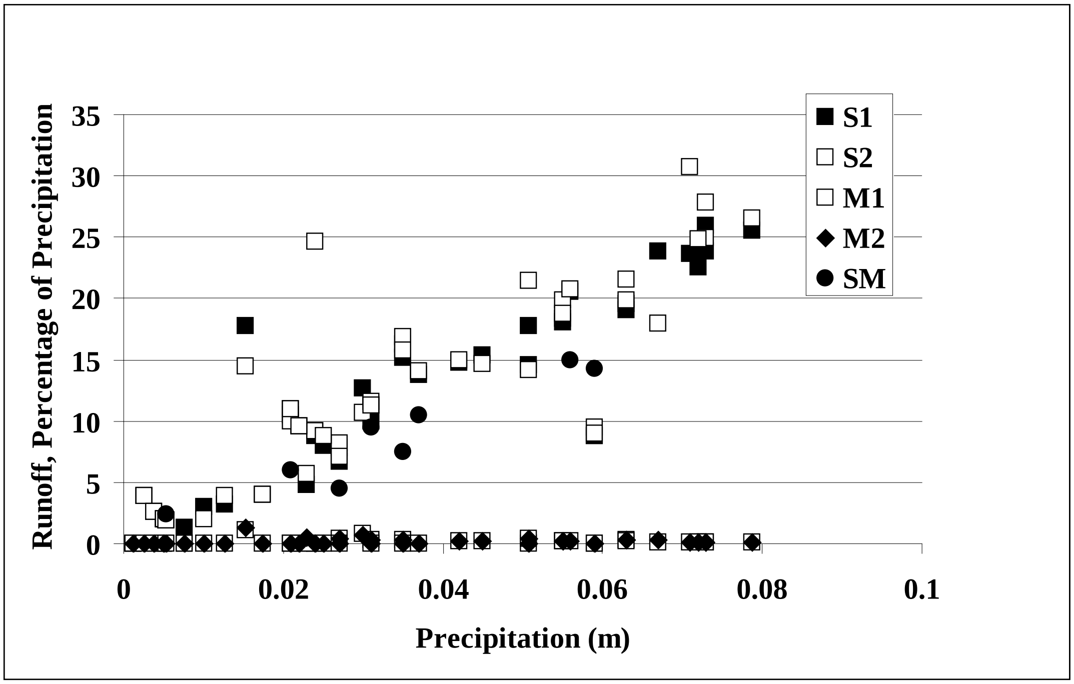


Figure 14. Runoff Behavior of Field Test Covers.

Not all of the infiltrating precipitation moved into the MSW layers; part of it was stored within the cover pores (Figure 15). Mulch covers had higher capacity for water storage, mainly because of its greater porosity (Chapter 3). Figure 15 shows an increase in water storage for mulch up to precipitation of 0.05 m when all pores are presumably filled. Soil covers on the other hand, reached their maximum storage at lower precipitation mainly because of their relatively lower porosity (42%). Precipitation intensity is another factor that dictates runoff and storage. However, in this study, the time frame for data collection was approximately 24 hours and the rate of precipitation was not recorded.

The mix cover behaved similarly to soil covers in terms of limiting infiltration and generating runoff, but like mulch covers in terms of storage capacity. Soil particles filled the pores between mulch particles reducing the porosity, and thus lowering the saturated hydraulic conductivity to half of that of mulch (Chapter 3). On the other hand, the high organic content and higher porosity of mulch fraction maintained the capability of mix covers to retain water.

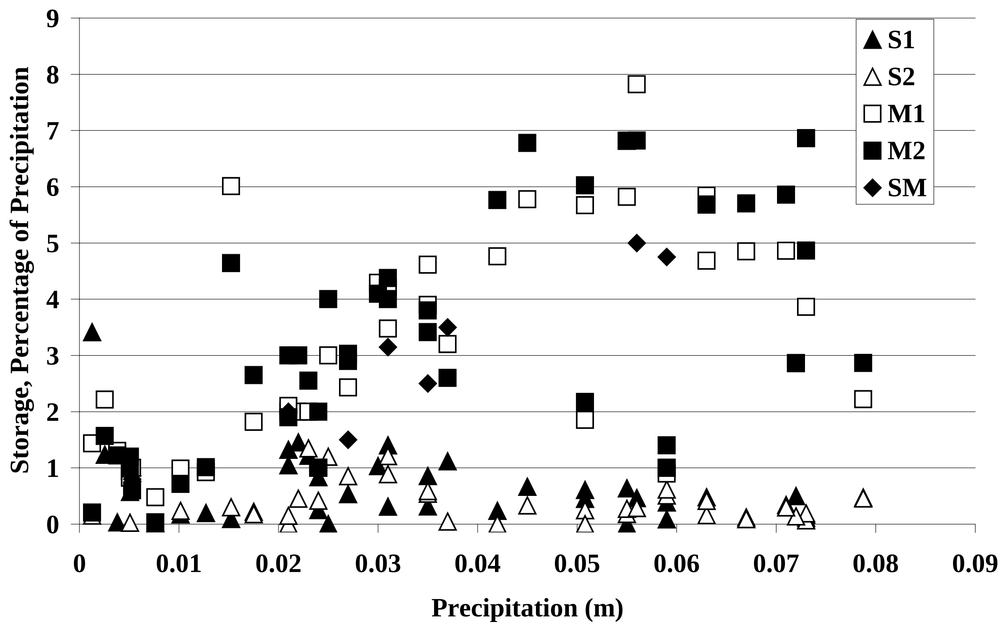


Figure 15. Water Storage Behavior of Field Test Covers.

Hydrologic Modeling

Field plots were simulated using HELP to calculate the generated runoff for precipitation data collected for the water balance field analysis. Modeling focused on infiltration through the cover system during the precipitation event to assess the ability of the covers to control leachate generation. Table 11 presents the hydrologic characteristics for the tested cover materials. HELP requires definition of the layers to be modeled in terms of material used, layer thickness, and function of layer. Table 12 presents the layers in the modeled profile.

Table 11. Hydrologic Properties of Tested Material.

	Porosity, v/v	**Saturated Hydraulic Conductivity, cm/sec**	**Curve Number[d], unitless**
Soil	0.42[a]	0.003[a]	79
Mulch	0.71[a]	0.12[a]	64
Mix	0.61[a]	0.04[a]	75
MSW	0.67[b]	6.1×10^{-5}[c]	NA

a: Chapter 3; b: HELP; c: Jain et al. (2006); d: calculated from the field data

Table 12. Profile Layers Modeled Using HELP.

Layer material	**Layer type**	**Thickness, cm**
Cover Material	Vertical drainage	30
Cover Material	Lateral drainage	30
MSW	Barrier	200
Soil	Lateral drainage	30
HDPE	Flexible membrane	0.015
Compacted Clay	Barrier	90

Figure 16 provides modeled infiltration plotted against the infiltration calculated from field testing. Data showed reasonably good correlation between modeled and experimental infiltration for soil covers (R^2=0.88), while had a low correlation for both mix and mulch covers (R^2=0.29, and R^2=0.03 respectively). Some data outliers were observed, particularly from mulch and mix plots. The model defines the maximum water storage of cover material according to the porosity. The stored water is released in the model as infiltration out of cover (and into the MSW layer) over an extended period of time (usually five days), while field water balance measurements were considered for a period of one day. Thus, higher porosities allow for wider variability in infiltration which might explain the greater scatter of infiltration data for mulch and mix covers as compared to the low porosity soil cover.

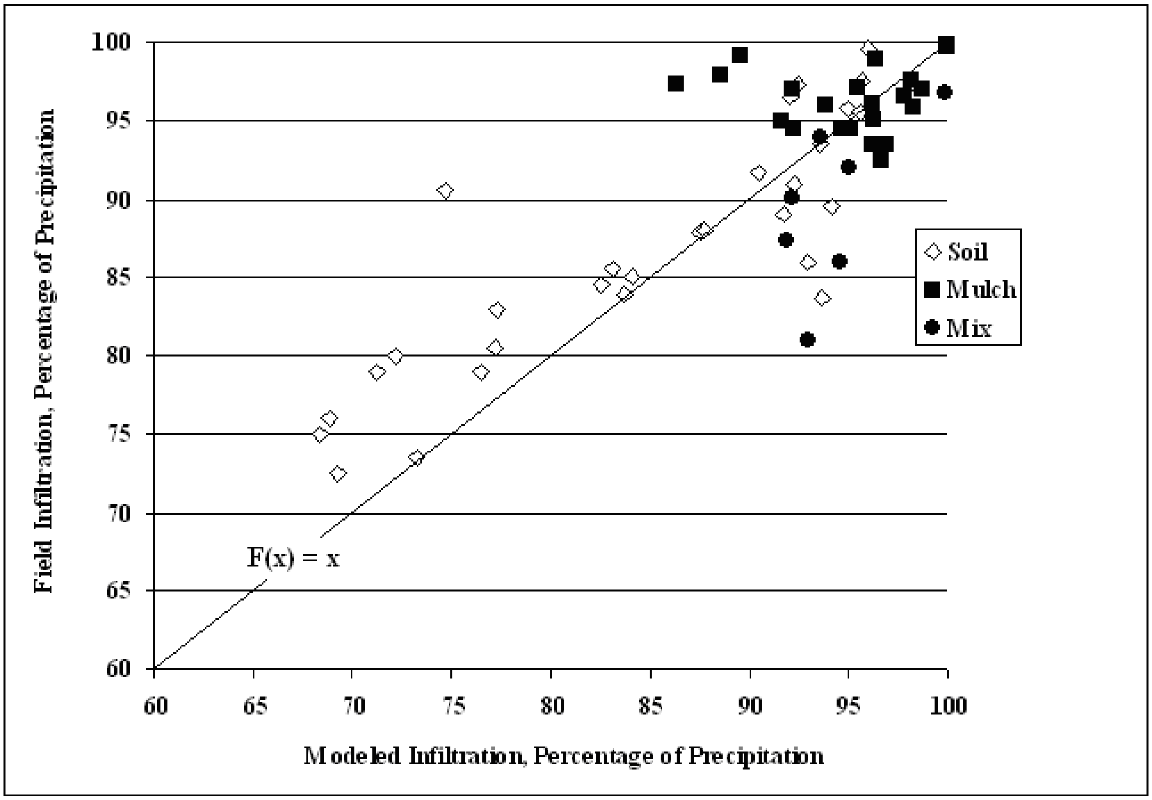


Figure 16. Comparison of Modeled and Field Infiltration Data.

Soil and mulch covers lost 3 and 8% of the original volume, respectively. Measured reduction in volume was related to degradation of the organic matter. However, since volume reduction was calculated depending on depth measurements of the cover, erosion of the top cover might also have contributed to loss of cover volume; especially in the case of soil covers. Mix cover lost 1% of the original volume, but it should be noted that mix cover was monitored for 282 days, while mulch and soil covers were monitored for 514 days. Mix cover is expected to lose more volume than soil covers if monitored for the same time period as soil covers, because of the greater organic fraction that mix cover has over soil covers, due to mulch particles.

Conclusions

Mulch covers showed greater capacity for VOC oxidation than soil and soil/mulch mixture covers due to the higher porosity of mulch than that of both soil and soil/mulch mixture. Mulch porosity is expected to decline as biological degradation continues leading to a lower aeration and removal efficiency. As a matter of fact, mulch covers experienced the highest volume reduction among the tested covers during the testing period. Volume reduction of mulch cover calculated in this study (in addition to previous calculations of reduction due to compaction, Chapter 3) suggests significant volume savings in landfills using mulch as ADC.

Percent VOC removal in mulch layers was found to decline with increase in loading; suggesting nonlinear Monod-like kinetics. However there were not enough removal data points to identify the point of oxidation saturation (or maximum removal capacity). Daily cover is not expected to provide VOC control because of the 200-day lag period observed in the field.

Both modeling and field water balance monitoring show greater control of infiltration into the landfill for soil and soil/mulch mixture covers than mulch covers due to the higher hydraulic conductivity of mulch. Field data showed that precipitation control for mulch covers was independent of rain depth, however, precipitation intensity was not measured in this study. Mulch is expected to increase in the ability to prevent water from infiltrating into the landfill with time as degradation occurs and porosity decreases. Mulch particles were found to decrease in size with time which allowed them to pack closer, decreasing porosity and hydraulic conductivity (Chapter 3). The mixed cover had soil-like behavior in terms of both VOC oxidation and infiltration control. It is possible that depending on the desired function of the cover, soil/mulch mixture covers can be prepared at different mixing ratios. In this study, HELP model was found to simulate actual infiltration through mix covers to an acceptable degree of accuracy. Thus, HELP model is suggested to be used in designing mulch/soil mixture covers with optimum behavior. However, simulation results will not take into consideration the effect of aging of the cover material.

References

Abichou, T., Chanton, J., Powelson, D., Fleiger, J., Escoriaza, S., Yuan, L., Stern, J. (2006). "Methane flux and oxidation at two types of intermediate landfill covers". Waste Management 26, 1305–1312.

Ait-Benichou, S., Jugnia, L., Greer, C., Cabral, A. (2009). "Methanotrophs and methanotrophic activity in engineered landfill biocovers". Waste Management 29 (2009) 2509–2517

Allen, R., Braithwaite, A., Hills, C. (1997). "Trace organic compounds in landfill gas at Seven U.K. waste disposal sites". Environmental Science Technology. 31:1054–1061

Abichou, T., Chanton, J., Powelson, D., Fleiger, J., Escoriaza, S., Yuan, L., Stern, J. (2006). "Methane flux and oxidation at two types of intermediate landfill covers". Waste Management 26 (2006), pp. 1305–1312.

ASTM D2216 - 10 Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass

Badv, K., Faridfard, R. (2005). “Laboratory determination of water retention and diffusion coefficient in unsaturated sand”. Water, Air, and Soil Pollution Journal 161(1–4):25–38.

Barlaz, M., Green, R., Chanton, J., Glodsmith D., Hater, R. (2004). “Evaluation of a biological active cover for mitigation of landfill gas emissions”. Environmental Science and Technology 38 (2004), pp. 4891–4899.

Berger, J., Fornés, V., Ott, C., Jager, J., Wawra, B., Zanke, U. (2005). “Methane oxidation in a landfill cover with capillary barrier”. Waste Management 25 (2005), pp. 369–373

Bender, M., Conrad, R. (1993) “Kinetics of methane oxidation in oxic soils”. Chemosphere 26; pp. 687–696.

Benson, C., Othman, M. (1993). “Hydraulic conductivity of compacted clay frozen and thawed in situ” Journal of Geotechnical Engineering 119 (1993), pp. 276–294

Boeckx, P., Van Cleemput, O. (1996). “Methane emission from a landfill and the methane oxidising capacity of its covering soil”. Soil Biology & Biochemistry 28(10-11): 1397-1405.

Boeckx, P., Van Cleemput, O., Villaralvo, I., (1997). "Methane oxidation in soils with different textures and land use". Nutrient Cycling in Agroecosystems 49, 91–95.

Bogner, J., Spokas, K. (1995). "Landfill as atmosperic methane sources and sinks". Chemosphere 31(9): 4119-4130.

Bogner, J., Matthews, E., Katzenstein, A., Blake, D., Carolan, M., (2000). "Greenhouse gas emissions from landfills: what we know and what we don't know". Proc ISWA World Cong 2000, pp 421–430

Bonito, D. (2005). "Trace elements in soil pore water: a comparison of sampling methods". Thesis submitted to the university of Nottingham, UK

Bracci, G., Paci, B., Giardi, M. (1995). "Paper mill sludge used a daily cover in landfills". Proceedings of Fifth International Landfill Symposium, Sardinia, 1995, pp. 897–904.

Bradley, D., Cook, J., Edwards, S., Johnston, G., Linforth, S., Taylor, J. (2001). "The control and measurement of landfill odours". Proceedings of Eighth International Landfill Symposium, Sardinia, 2001. 681–690.

Carson, D. (1992). “Municipal solid waste landfill daily cover alternatives”. Geotextiles and Geomembranes 11, pp. 629–635.

Cassel, D.K., Nielsen, D.R. 1986. “Methods of Soil Analysis: Part 1. Physical and Mineralogical Methods”. 2nd edn. American Society of Agronomy, Madisan, WI, pp. 901-926.

Clarholm M. 1 984. “Heterotrophic, freeliving protozoa: neglected microorganisms with an important task in regulating bacteria populations”. p. 321-326. In M. J. Klug and C. A. eddy (edition), Current perspectives in microbial ecology. American Society for Microbiology, Washington, D.C.

Czepiel, M., Mosher, B., Crill, M., Harriss, C. (1996). “Quantifying the effect of oxidation on landfill methane emissions”. Journal of Geophysical Research. 1996, 101 (D11), 16721

Czepiel, M., Crill, C., Harriss, C. (1993). “Methane emissions from municipal wastewater treatment processes”. Environmental science and technology, 27: 2472-2477.

De Visscher, A., Thomas, D., Boeckx, P., Van Cleemput, O. (1999). “Methane oxidation in simulated landfill cover soil environments”. Environmental science and technology 33:1854–1859

De Visscher, A., Schippers, M., Cleemput, O. (2001). “Short-term kinetic response of enhanced methane oxidation in landfill cover soils to environmental factors” Biology and fertility of soils (2001) 33:231–237

Fredlund, G. (1995). “The scope of unsaturated soil problems. In: Alonso EE, Delage P, Balkema AA (eds)” Proceedings of the 1st international conference on unsaturated soils, vol 3. Rotterdam, The Netherlands, pp 869–876

Fredlund, G., Rahardjo, H. (1993) “Soil mechanics for unsaturated soils”. Wiley, USA

Graf, M. 2007. “Influence of physical parameters on methane oxidation in landfill cover soils”. Term Paper in Biogeochemistry and Pollution Dynamics, Master Studies in Environmental Science, ETH Zürich

Hancock, J., Newman, S., Chadwick, B. (1999). “Mulched woody material mixtures: an improved performance daily cover”. Proceedings of Seventh International Landfill Symposium, Sardinia, 1999, pp. 365–372.

Hanumantha Rao, B., Sridhar, V., Rakesh, R., Singh, D., Narayan, P., Wattal, P. (2009). “Application of In-situ Lysimetric Studies for Determining oil Hydraulic Conductivity”. Geotechnical and Geological Engineering (2009) 27:595–606

Haughey, R. (2001). “landfill alternative daily cover: conserving air space and reducing landfill operating cost”. Waste Management and Research 19 (2001), pp. 89–95.

Huber-Humer, M., (2004). “International research into landfill gas emissions and mitigation strategies – IWWG working group [CLEAR]”. Waste Manage. 24, 425– 427.

Huber-Humer, M., Gebert, J., Hilger, H. (2008). “Biotic systems to mitigate landfill methane emissions”. Waste management and research 26, 33–46. doi:10.1177/0734242X07 087977.

Hurst, C., Longhurst, P., Pollard, S., Smith, R., Jefferson, B., Gronow, J. (2005). “Assessment of Municipal Waste Compost as a daily cover material for odour control at landfill sites”. Environment pollution, Volume 135, Issue 1, May 2005, Pages 171-177.

Humer, M., Lechner, P. (2001). “Microbial methane oxidation for the reduction of landfill gas emissions”. solid waste Technology and Management. 27, 146–151.

Hughes K.L., Hughes A.D., Joe E.H. “Landfills: Science and Engineering Aspects”. Ohio State University, Extension Fact Sheet: Community Development.CDFS-137-05

Ishigaki, T., Yamada, M., Nagamori, M., Ono, Y., Inoue, Y. (2005). “Estimation of methane emission from whole waste landfill site using correlation between flux and ground temperature”. Environmental Geology 48: 845–853

Jain, P., Powell, J., Townsend T., Reinhart D.R. (2006). “Estimating the hydraulic conductivity of landfill municipal solid waste using the borehole permeameter test”. Environmental engineering, June 2006.

Jang, Y., Kim Y., Lee S. (2002). “Hydraulic properties and leachate level analysis of Kimpo metropolitan Landfill, Korea” Waste Management, 22, 261- 267.

Jugnia, L., Cabral, A., Greer, C. (2008). “Biotic methane oxidation within an instrumented experimental landfill cover”. Ecological Engineering (33) 2008 102-109

Keller, A. (1988). “Trace Constituents in Landfill Gas-task report on inventory and
assessment of cleaning technologies”. Gas Research Institute, Chicago, ILL., Report no. GRI-87/001 8.2., April, 140pp.

Kienbusch, M. (1986). “Measurement of Gaseous Emission Rates from Land Surfaces Using an Emission Isolation Flux Chamber”. Work performed by Radian Corp. under U.S. EPA contract no. 68-02-3889.

Kightley, D., Nedwell, D., Cooper, M. (1995). “Capacity for Methane Oxidation in Landfill Cover Soils Measured in Laboratory-Scale Soil Microcosms”. Applied and Environmental Microbiology, Feb. 1995, p. 592–601

Khire, M.V., Benson, C.H., Bosscher, P.J. (1997). “Water Balance Modeling of Earthen Final Covers”. Geotechnical and Geoenvironmental engineering August 1997.

Kreith, F. (1995). “Handbook of Solid Waste Management”. McGraw-Hill, New York, pp. 1211–1213.

Liu, X. (2004). “Design of cost-effective lysimeter for field valuation of alternative landfill cover projects using ydrys 2D simulation”. Ph. D. thesis submitted to the department of Civil and Environmental Engineering. Florida State University, USA

Lu, N., Likos, J. (2004). “Unsaturated soil mechanics”. Wiley, Hoboken, NJ

Mancinelli, R. (1995). “The regulation of methane oxidation in soil”. Annual review of microbiology. 49:581-605

Molins, S., Mayer, U., Scheutz, C., Kjeldsen, P. (2008). “Transport and reaction processes affecting the attenuation of landfill gas in cover soils”. Journal of Environmental quality 37:459-468.

Mosher, W., Czepiel, M., Harriss, C., Shorter, H., Kolb, E., McManus, B., Allwine, E., Lamb, K. (1999). “Methane emissions at nine landfill sites in the northeastern united states”. Environmental Science and Technology 33 (1999), pp. 2088–2094.

P.R. Schroeder, J.M. Morgan, T.M. Walski and A.C. Gibson, “Hydrologic Evaluation of Landfill Performance (HELP) Model: Volume I. User's Guide for Version 1. Draft Report”. EPA/530-SW-84- 009, U.S. Environmental Protection Agency, Municipal Environmental Research Laboratory, Cincinnati, Ohio, 1984a.

Radian Corporation. (1986). “Measurement of Gaseous Emission Rates From Land Surfaces Using an Emission Isolation Flux Chamber User's Guide, EPA Contract No. 68-02-3889”.

Roy, W., Parkin, W., Wagner-Riddle, C. (2000). “Water flow in unsaturated soil below turfgrass: observations and LEACHM (within EXPRES) predictions”. Soil Science Society of America Journal 64:86–93

Singh, N., Kuriyan, J. (2003). “Estimation of unsaturated hydraulic conductivity using soil suction measurements obtained by an insertion tensiometer”. Canadian Geotechnical Journal 40(2):476–483. doi:10.1139/t02-112

Singh, N., Kuriyan, J., Madhuri, V. (2001). “Application of a geotechnical centrifuge for estimation of unsaturated soil hydraulic conductivity”. Testing and evaluation 29(6):556–562

Shimaoka, T., Miyawaki, K., Hanashima, M., Tsuji, H., Ito, H. (1997). “Impact of daily cover soil on the stabilisation of a landfill”. Proceedings of Sixth International Landfill Symposium, Sardinia, 1997, pp. 341–350.

Sreedeep, S., Singh, N. (2005). “A study to investigate influence of soil properties on its suction”. Testing and evaluation 31(1):579–584

Stern, J.C., Chanton, J., Abichou, T., Powelson, D., Yuan, L., Escoriza, S., Bogner, J. (2007). “Use of a biologically active cover to reduce landfill methane emissions and enhance methane oxidation”. Waste Management 27 (9), 1248–1258.

Thakur, S., Sreedeep, S., Singh, N. (2006). “Laboratory investigations on extremely high suction measurements for fine-grained soils”. Geotechnical and Geological Engineering 24(3):565–578. doi:10.1007/s10706-005-1147-5

Thomasson, J., Wierenga, J. (2003). “Spatial variability of the effective retardation factor in an unsaturated field soil”. Hydrology 272:213–225

USDA, Soil Conservation Service. (1985). "National engineering handbook, section 4, hydrology". US Government Printing Office, Washington, D.C.

U.S. Environmental Protection Agency. "Non-CO2 Greenhouse Gas Emissions from Developed Countries". EPA-430-R-01-007; U.S. EPA: Washington, DC, 2001.

U.S. Environmental Protection Agency. "U.S. Greenhouse Gas Inventory Report (2010). Inventory of U.S. greenhouse gas emissions and sinks: 1990-2008".

Visvanathan, C., Pokhrel, D., Cheimchaisri, W., Hettiaratchi, P., Wu, S. (1999). "Methanothropic activities in tropical landfill cover soils: Effects of temperature, moisture content and methane concentration". Waste management and research 17, 313–323.

Watzinger, A., Reichenauer, G., Blum, H., Gerzabek, H., Zechmeister–Boltenstern, S. (2005). "The effect of landfill leachate irrigation on soil gas position: methane oxidation and nitrous oxide formation". Water, Air, and Soil Pollution 164 (2005), pp. 295–313

Whalen, C., Reeburgh, S., Sandbeck, A. (1990). "Rapid methane oxidation in a landfill cover soil". Applied and environmental microbiology 56, 3405–3411.

CHAPTER 5: LIFE CYCYLE ASSESSMENT OF GREEN WASTE MANAGEMENT PROCESSES

Introduction

Management of Green Waste

Management of green waste is a significant challenge in the US, where, in 2008, green waste was reported to be 13.2% of the 250 million tons of municipal solid waste (MSW) (USEPA, 2008). Because of its volume and potential use as a soil amendment, the disposal of green waste in lined landfills is banned in most states. In Europe, it is required that landfilling of biodegradable MSW be reduced by 65 percent by 2020 (European Commission 2009), which has placed greater emphasis on waste-to-energy and recycling.

Consequently, green waste is frequently composted, combusted, or mulched in preparation for recycling. Grass-rich green waste can cause odor issues at composting facilities if improperly stored. Therefore, municipalities are investigating alternative strategies to reduce green waste volumes during peak periods such as encouraging residents to leave clippings on the lawn and direct application of green waste to agricultural land (Uhlar-Heffner et al., 1998). In Florida, a number of waste management facilities (WMF) offer ground green waste (mulch) to the public to be used for agricultural and horticultural purposes. Most green waste is a beneficial soil amendment because it is a source of plant nutrients and organic matter. Allowing public access to mulch prior to composting also provides an outlet for handling high volumes of materials at compost facilities (Bary et al. 2005). Green waste without further processing has been used on a variety of crops in western Washington, including sweet corn, silage corn, rhubarb, flower bulbs, cabbage, and squash (Cogger et al. 2002).

Storage of green waste for extended periods of time (more than a week) should be avoided to prevent odor generation (Cogger et al. 2002). Despite the low cost of managing green waste as mulch as opposed to composting, the quality of the fresh mulch as a soil conditioner/fertilizer is poor (Cogger et al. 2002); fresh mulch contains weed seeds and non-degradable material, and if not screened, excessive fractions of large particles. Also, from an energy consumption point of view, the numerous trips by private vehicles picking up mulch has a higher environmental impact than fewer trips carried out by large vehicles delivering compost to a commercial point of sale and use.

This study investigates the environmental impacts associated with three green waste management processes; use as alternative daily cover (ADC), use as biofuel, and composting, through Life Cycle Assessment (LCA). The three management options were compared in terms of greenhouse gas (GHG) impacts.

Use of Mulch as Alternative Daily Cover (ADC)

According to Subtitle D of the Resource Conservation and Recovery Act (RCRA) codified in the Code of Federal Regulation (CFR) 258.21 Section (a); landfill owners and operators are required to cover the active face of the landfill with a minimum of 15 cm of earthen material at the end of every day (or at more frequent intervals if necessary) to control disease vectors, fires, odors, blowing litter, and scavenging. Many landfill operators must import cover soil from outside of the facility, increasing operating costs. Section CFR 258.21(b) allows the use of alternative cover materials if the landfill owner or operator demonstrates that the alternative material and thickness will function the same as a soil cover and does not present a threat to human health and the environment.

In 2001, the California Assembly passed a bill that allows green wastes to be used as ADC to be counted as part of the recycling effort of a community (Haughey, 2001). In 2009, an estimated 2.1 million tons of source-separated green wastes were shredded and used as ADC in landfills (Kaufman and Themelis, 2009). Use of mulch as landfill daily and intermediate cover is expected to save 6% of the landfill total volume; since overburden pressure, compaction, and biological degradation could reduce mulch volume by as much as 52% of its original volume (Chapter 3 and 4). Additional volume reduction of mulch layers is expected to occur after the biological degradation of organic fractions.

Use of mulch as ADC enhances control of methane emissions as compared to soil covers due to the relatively high porosity of mulch which allows better oxygen diffusion to support aerobic methanotrophic activity (Chapter 4; Abichou et al., 2006; Stern et al., 2007; Humer and Lechner 1999; Hilger and Humer 2003; Barlaz et al., 2004). Replacing soil reduces both costs and environmental burdens related to soil excavation (CIWMB, 2009) and has potential for carbon sequestration.

Vegetative mulch has relatively high hydraulic conductivity compared to soil due to the greater particle angularity and size and consequential higher porosity. Therefore, mulch covers are expected to act poorly in controlling precipitation infiltration, generating greater amounts of leachate. Also, mulch will initially decompose aerobically, however, anaerobic conditions will eventually prevail and methane may be emitted until landfill gas (LFG) collection wells are installed. USEPA regulations require installation of gas collection wells within two years after final cover has been placed or five years after initial disposal of waste.

Combustion with Energy Recovery

The United States is currently the largest producer of electricity from biomass fuels having more than half of global installed capacity of biomass power plants. Biomass fuels 1.5% of the total electricity supply compared to 0.1% for wind and solar combined. More than 7800 MW of power are produced in biomass power plants installed at more than 350 locations in the U.S. (International Energy Agency, 2008).

The potential environmental benefits from replacing petroleum fuels by renewable biomass sources are the main driving forces for promoting the production and use of biofuels and bioenergy (Cherubinia et al. 2009). Vegetative mulch is considered a biofuel generated through biowaste, as opposed to biofuels supplied by dedicated energy crops (Hoogwijk et al. 2009). Energy crops require agronomic care to increase the yield (higher frequency of tillage, higher quantity of fertilizers, more frequent irrigation), which increases GHG emissions (Cherubini 2009), as opposed to diversion of biowaste to energy recovery option since they are not specifically produced for use as an energy source (Khanal et al. 2010). The diversion of mulch from landfills can also reduce environmental impacts associated with fugitive methane emissions from anaerobic decomposition. However, removing yard waste from fields (agricultural residues) for use as biofuel could affect the carbon pool and ultimately the agricultural yield (Cherubini et al. 2009).

Composting

Composting involves the aerobic biological degradation of ground green waste to a soil-like material which is a beneficial additive to soils. In 2008, 64.1% of generated yard waste was composted at 3,500 composting facilities mostly located in the Northwest and Midwest (USEPA, 2008). Of the three predominant composting technologies; windrow composting, aerated static piles, and in-vessel aerobic composing, windrow composting is the most common practice (Haaren et al. 2009). Addition of compost to soil improves soil water-holding capacity, drainage and aeration, and it also increases the percentage of organic materials and nutrients in soils.

Agricultural application of compost can reduce fertilizer use, the extent of which depends on the compost quality and nutrient content (Barlaz et al. 2003, Haaren et al. 2010). Compost benefits, such as reduced plant disease, conserved soil water, and decreased leaching of water-soluble soil nutrients, can offset use of fungicides, water for irrigation, and fertilizers and reduce nonpoint sources of water pollution. However, these offsets, due to the inconsistency of compost quality, are difficult to quantify (Barlaz et al. 2003). During the composting process, emitted gasses, including NH_3, volatile organic compounds (VOCs), N_2O, CH_4, and other compounds that contribute to global warming, acid rain, human and environment toxicity, and to the promotion of photochemical oxidation reactions in the atmosphere have been a concern (Komilis et al. 2003, Hellebrand and Kalk 2001, Pagans et al. 2006).

Carbon Sequestration

Atmospheric level of CO_2 has increased by 31% from pre-industrial level (IPCC 2010). Evidence suggests this observed rise in atmospheric CO2 levels is due primarily to expanded use of fossil fuels for energy. In the US, landfills are the second largest anthropogenic source of carbon (as CH_4), accounting for 22% of total US methane emissions (IPCC 2010).

Anaerobic conditions, which normally prevail in landfills, are not conducive to the decomposition of lignin or to cellulosic material protected by lignin (Aragno 1988, Barlaz et al. 1989, Barlaz et al. 1990, Cummings and Stewart 1994, Ham et al. 1993, Khan 1977, Pfeffer and Khan 1976, Suflita et al 1992, Wang et al. 1994, Young and Frazer 1987). Consequently, much of woody materials and other wastes which are primarily lignin and cellulose, will remain in the landfill for very long periods of time. Therefore, the use of mulch as alternative daily cover in landfills potentially provides a sink for carbon (Barlaz, 1998). In order to quantify the carbon sequestration in landfills, the percentage of carbon degradation in organic waste must be estimated. Barlaz (2008) reported that green waste has a carbon storage factor of 0.38 g carbon sequestered/g dry green waste. Thus, while landfills tend to contribute large amounts of greenhouse gases, to some extent these emissions could be offset by carbon sequestration.

Composting, on the other hand, has lower levels of carbon sequestration because of the efficient aerobic degradation process.

LCA in Solid Waste Management

LCA is an important tool for consideration of both direct and indirect impacts of waste management technologies and policies (Thorneloe et al. 2002, 2005, WRAP 2006). LCA models have been developed based on a collection of data from laboratory and field research to construct a comprehensive inventory of solid, liquid and gas emission factors, energy flows, and costs of waste management processes, such as landfilling, incineration, recycling, composting, anaerobic biodegradation, and gasification. Other tools that have been used to assess waste management options are the WAste Reduction Model (USA), ARES (Germany), EPIC/CSR (Canada), IWM2 (UK), and ORWARE (Sweden). Each model, however, has different system boundaries, waste characteristics, technologies included, beneficial offsets, and approaches to assess the associated emissions (Bhander et al., 2006). The combination of environmental impacts also are substantially different in the models; some cover a large range of environmental impacts and some are only Life Cycle Inventories (LCI) models and consider solid, liquid, and gaseous emissions factors.

Finnveden et al. (2004) produced a LCA that compares recycling, anaerobic digestion, composting, incineration and landfilling in terms of their effects on energy consumption, GHG emissions, and acidification. However, there was no consideration of the carbon sequestration achieved through landfilling and composting; only the fate of combustible and compostable fractions of waste was considered in this study. Recycling of paper and plastic materials was found to be favorable in terms of energy consumption and GHG emissions, while incineration was found to be favorable over landfilling in terms of energy use and GHG emissions.

Cabaraban et al. (2008) conducted a LCA that compares aerobic in-vessel composting with bioreactor landfilling of food waste and green waste. The study was focused mainly on energy recovery, GHG emissions, waterborne emissions contributing to aquatic toxicity, air emissions contributing to human toxicity, and on the economic feasibility of the two processes. It was found that the bioreactor landfill is a favorable option over in-vessel composting.

Haight (2005) compared in-vessel biogasification and composting with traditional landfilling of biodegradable waste fractions using LCA. Impacts considered were energy consumption (or recovery), residue recoveries, and emissions to air and water. Results showed that anaerobic degradation of the organic fraction of waste and the resulting energy recovered makes this process superior to composting.

Kaplan et al. (2008) evaluated the solid waste management taking place in the state of Delaware from economic and GHG emission points of view and compared various scenarios of management that included recycling, landfilling, combustion, and composting, using the EPA Decision Support Tool (DST). Results showed that applying landfill diversion strategies (e.g., curbside recycling) for only a portion of the population is most cost-effective for meeting a county specific landfill diversion target, while implementation of waste-to energy offers the most GHG emission reductions.

Komilis and Ham (2004) worked on a LCI for composting three types of organic waste fractions; high quality (HQ), low quality (LQ), and green waste (YW). The study focused on total management costs and on precombustion and combustion energy requirements. Total costs for the LQ, HQ, and the YW were approximately $US30/ton, $US50/ton, and $US15/ton, respectively. Total energy requirements were 97, 167, and 29 kWh/ton for LQ, HQ, and YW, respectively.

Haaren et al. (2010) compared the environmental impacts of composting green wastes in windrows with using them in place of soil as ADC in landfills. The LCA showed that the ADC scenario is better for the environment than windrow composting only in cases where the landfill is equipped with gas collection system. Otherwise, the environmentally preferable method for disposal of source-separated green wastes is composting.

Methodology

LCA Model Inputs and System Boundaries

In this study, a LCI was prepared for GHG emissions and carbon sequestration related to the three management process of green waste and their offsets. Figure 17 shows the system boundary of the study. However, this LCA does not consider economics related to construction of a BTE facility, landfill, or composting facility, it only focuses on carbon fate and GHG emissions post green waste grinding. Various input data sources were used (AP-42, 1998; EREF 1998; USEPA, 1991; USEPA, 1994; Barlaz, 1997; Barlaz, 2009; Tchobanoglous et al., 1993; and Taylor et al., 1988). No emissions associated with spreading of mulch cover were considered; since it is a process that trucks and compactors already does regardless of the cover material. Also, combustion of green waste does not require prior processing, since the LCA functional unit defines the green waste as already grinded. However, composting involves processes that generate GHG (i.e., turning and screening) that should be accounted for. The EPA DST model was used to calculate emission factors related to composting processes. The DST is a tool designed for use in evaluating community level MSW management strategies (DST User Manual 2000). The EPA DST has been developed by Research Triangle Institute RTI International and its partners (including North Carolina State University and the University of Wisconsin) in collaboration with the EPA National Risk Management Research Laboratory (NRMRL).

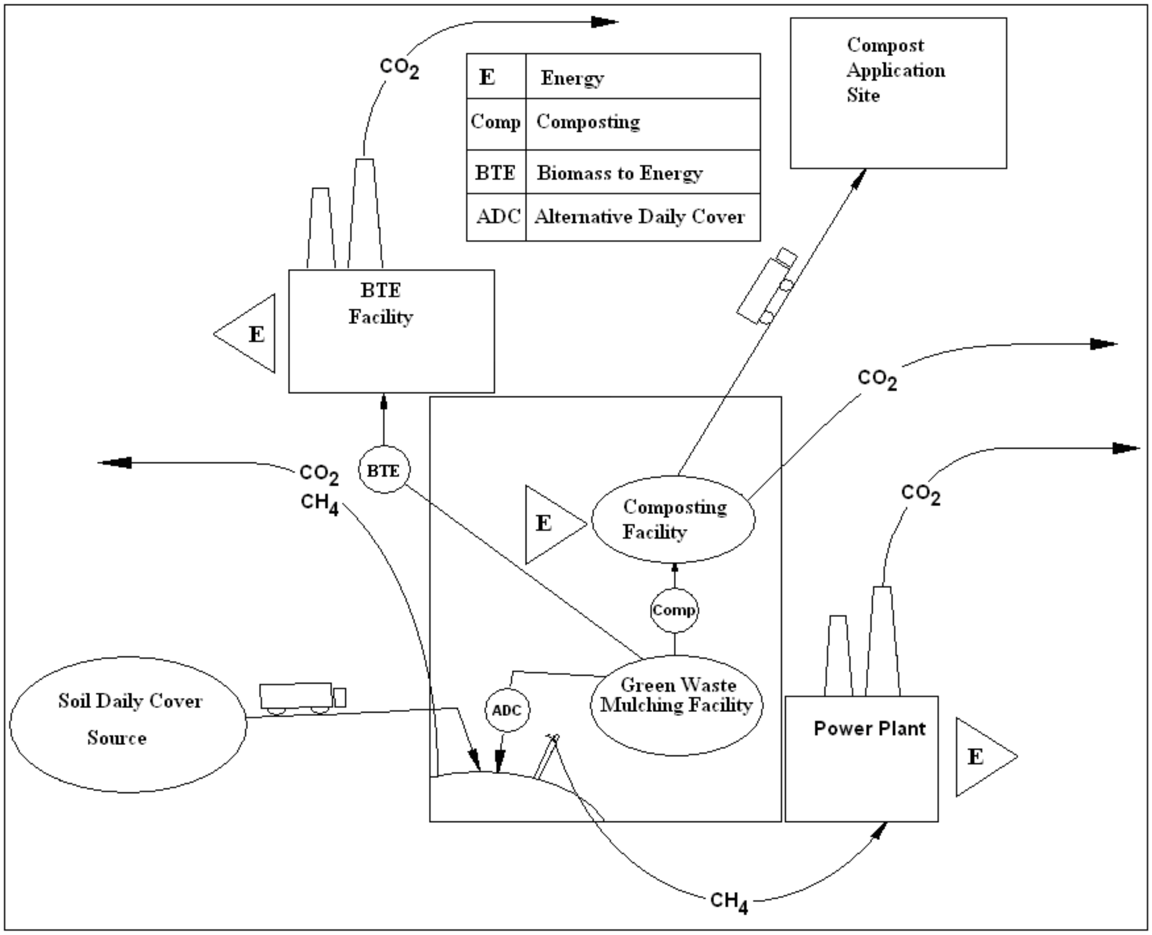


Figure 17. LCA System Boundary showing Energy flows and emissions.

The three management options for green waste considered are discussed below. Table 13 lists inputs required for calculating the emissions. The functional unit of this study is one metric ton of dry shredded green waste (mulch). The analysis captures material flows of the functional unit for the management options for 100 years. The analysis excludes the emissions related to shredding and transporting green waste to the WMF because these are common to the three alternatives. Other fuel-based power plants were considered for assessing variation in GHG offsets for different types of power plants. GHG emission offsets for energy replacement were calculated based on replacing electricity generated from a coal-based power plant.

Several authors (Hauschild and Wenzel, 1997; Nielsen and Hauschild, 1998; Finnveden et al., 2004) consider landfill CO_2 emissions a result of a natural process from the biodegradable fractions of waste that do not need to be considered as a net contribution to the global warming impact category (biogenic emissions); since, eventually, it will be returned to the carbon cycle throw plant growth. However, the carbon (stored in plants) might be released again in the form of methane if landfilled. Excluding biogenic emissions from net GHG emissions will underestimate the impacts of the process generating those emissions at the first place. Accounting for the global warming potential of a process can only be achieved by considering, in addition to non-biogenic emissions, both biogenic emissions and sequestered carbon in that process and converting the stored carbon it to negative GHG emissions. Blengini (2008) argues that when considering alternative management options, with different potentials of carbon dioxide generation, excluding the biogenic emissions can dramatically distort the results.

For this reason, in this study, two approaches have been adopted in considering biogenic emissions. The first approach assumed that biogenic emissions of CO_2 do not have a global warming potential. This is in accordance with IPCC (2006) recommendations, based on the assumption that in a long-term LCA-perspective (i.e., long enough to allow a full degradation of organic matter); biogenic emissions of CO_2 are actually balanced by an equivalent biological uptake of CO_2 during plant growth. The other approach accounted for both biogenic emissions as GHG and carbon sequestration. Carbon that has been stored is converted into CO_2-equivalent emissions (multiplying by 44/12) and subtracted from biogenic emissions. Previous studies (Haaren et al., 2010; Blengini, 2008) followed this approach accounting for carbon sequestration by converting sequestered carbon to negative biogenic CO_2 emissions while at the same time accounting for the biogenic emissions of the analyzed processes.

Table 13. Input Values Used in the LCI.

Green Waste Management Process		Source
ADC		
LFG collection system efficiency, %	75	Barlaz et al. (2009)
Landfill first order decay rate constant, Year^{-1}	0.04	AP-42 (1998)
Methane yield[a] for grass, g CO_2-eq/ton dry green waste	731,000	
Methane yield[a] for leaves, g CO_2-eq/ton dry green waste	165,000	
Methane yield[a] for branches, g CO_2-eq/ton dry green waste	337,000	Barlaz (1997)
Methane destruction during flaring, %	99	
Methane heat value, MJ/kg CH_4	46.5	
Soil excavation emissions, g CO_2-eq/ton soil	4,300	EREF[b] (1998)
Combustion		
Heat value of Grass, kJ/ton green waste	6,000,000	
Heat value of leaves, kJ/ton green waste	6,000,000	
Heat value of branches, kJ/ton green waste	15,000,000	Tchobanoglous et al. (1993)
Coal-based power plant offset, g CO_2-eq/kWatt-hr	1,035	EREF[b] (1998)
Composting		
Compost processing emissions for grass, g CO_2-eq/ton green waste	7,410	
Compost processing emissions for leaves, g CO_2-eq/ton green waste	7,560	
Compost processing emissions for branches, g CO_2-eq/ton green waste	7,620	Taylor et al. (1988), USEPA (1994)
Transportation		**Source**
Transportation emissions, g CO_2-eq/Km	36.2	
Volume of truck, m^3	15.3	
Truck efficiency, km/liter	2.13	
Fuel pre-combustion emission g CO_2-eq/liter	325	USEPA (1991)

a: Based on BMP values provided by source. b: Environmental Research and Education Foundation.

LCA of Mulched Green Waste Use as ADC

Carbon balance calculations were based on the assumption that when green waste is landfilled, the carbon was sequestered, emitted as biogenic CO_2, or emitted as CH_4. Barlaz (1997) laboratory tests show that when green waste is landfilled, 77% of carbon is stored. Methane generation was based on the ultimate yield values used by the EPA-DST for green waste, which were based on laboratory-measured gas yields under highly controlled conditions (Barlaz 1997). Collected methane was then converted to biogenic CO_2, through flaring for power generation, assuming a 99% destruction of methane. Carbon that is not sequestered nor emitted as methane was assumed to be released as biogenic CO_2. However, it should be noted that methane emissions were based on a conservative calculation; not considering the oxidation of methane through the mulch covers which will decrease the values of methane emissions and increase that of biogenic CO_2.

LFG collection efficiencies range from 50% to 90%, depending on the cover type and extent of the collection system. However, it is preferable to use an overall average efficiency considering the total gas production and collection over the entire life of the landfill (Barlaz 2009). Collected gas was either flared (ADC/Flaring) or used to generate electricity (ADC/Energy); where the generated power replaced that of coal-based power plant. Coal fueled power plants are the major type of power generating facilities; represent 56% of the total power plants in US, followed by Nuclear power plants (22%) (EREF 1998).

Emission savings due to avoided soil excavation for daily cover included air emissions from diesel fuel production (pre-combustion) and diesel fuel combustion in heavy equipment. Replaced soil was assumed to have a negligible organic fraction and therefore generated no methane when landfilled.

LCA of Mulch Combustion in a Biomass to Energy (BTE) Facility

Kranert et al. (2009) assumes 100% oxidation of the green waste carbon when burned as a biofuel. Thus, no carbon sequestration or methane emissions were calculated for green waste combustion in a BTE. Tchobanoglous et al. (1993) calculated the fractional mass composition of the major chemical elements in dry green waste. Accordingly, Haaren et al. (2010) proposed the chemical formula for one mol of dry green waste to be $C_{3.83}H_{5.95}O_{2.38}N_{0.24}S_{0.009}$. One ton of dry green waste was calculated to produce approximately 1.8 Mg CO_2-eq, under complete oxidization.

A BTE facility was assumed to exist at the site of green waste management, therefore, any emissions that are related to either construction of the facility or transportation of mulch to the facility were not considered. Energy recovered from mulch combustion was assumed to be in the form of electricity, and gaseous emissions were related to combustion of mulch. Offsets included avoided emissions due to reduced electricity generation by power plants.

LCA of Composting

Composting only sequesters 2% of green waste carbon (EPA 2002), and methane generated in windrows composting was assumed to be negligible because of the efficient turning (Komilis and Ham 2004). Green waste carbon that was not stored was assumed to be released as biogenic CO_2.

A windrow composting facility was assumed to exist at the site of green waste management, eliminating emissions related to construction and transportation from consideration. It was assumed that plastic bags with leaves and grass clippings were manually opened and removed upon reaching the facility. The windrows were turned monthly using a front-end loader.

If oxygen fails to penetrate the windrow, composting leads to odor and methane generation. Hence, the composting pad is typically uncovered, and no odor-control system is installed. A post-composting trommel screen produces a more marketable green waste-derived compost, therefore its emissions are considered. Compost is transported to application sites outside the WMF and the effect of hauling distance on the LCA was analyzed. In this study, GHG emissions were related to diesel requirements for turning and screening of produced compost and for transportation of finished product.

Results and Discussion

Figure 18 shows the fate of carbon in green waste for each management process including biogenic CO_2 emissions, CH_4 emissions, and sequestered-carbon. Carbon in green waste is best sequestered through landfilling (77%), and is totally released through combustion.

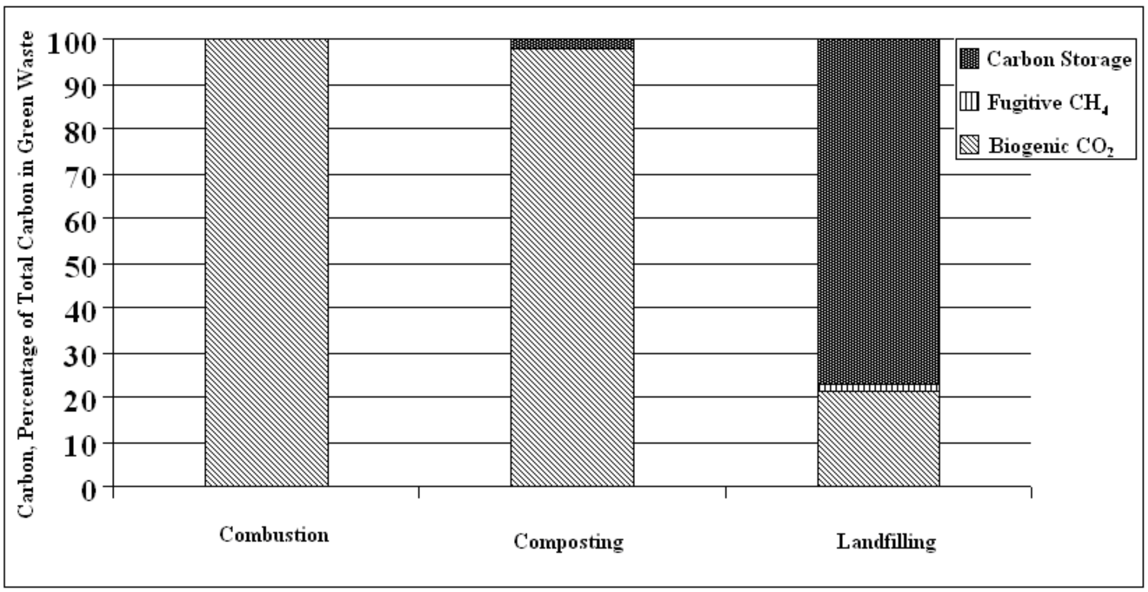


Figure 18. Green Waste Carbon Balance for the Management Options.

Figure 19 shows the net GHG emissions accounting only for methane and non-biogenic emissions and offsets. Landfilling had the highest GHG emissions due to the fugitive methane emissions related to the anaerobic degradation in landfills. Flaring and utilizing LFG for energy recovery at a gas-based power plant convert methane into biogenic CO_2. Combustion and composting processes of green waste generated biogenic CO_2 only and insignificant amounts of methane.

Combustion of green waste in a BTE facility had much higher GHG emission offsets than energy utilization of LFG, because of the higher heat rate of burning green waste directly. In LFG energy recovery, only the biodegradable part of waste is contributing to gas generation, and there are significant inefficiencies in the gas collection system (Kaplan et al. 2008). As a matter of fact, 1 ton of dry green waste was calculated to generate 14,500 MJ when burned, while burning the collected methane produced from landfilling 1 ton of dry green waste was calculated to generate only 577 MJ.

The effect of hauling distance on the total net GHG emissions of composting per functional unit was assessed. Non-biogenic GHG emissions increased by approximately 375 g CO_2-eq/ton green waste for every additional 10 kilometer of hauling distance, which was found to be insignificant compared to composting non-biogenic emissions.

Accounting for biogenic emissions and carbon sequestration dramatically changes the conclusions drawn from the LCA. Figure 20 shows the net emissions accounting for both carbon sequestration (as CO_2-eq emissions) and biogenic CO_2 emissions. Both Landfilling/Flaring and Landfilling/Energy appear to have the lowest GHG emissions, mainly because of carbon sequestration. BTE, which had the highest GHG offsets when biogenic emissions and carbon sequestration were excluded, generates positive GHG emissions due to release of all the carbon in green waste as CO_2 emissions. Composting resulted in the highest GHG emissions after considering the biogenic emissions generated and the low carbon sequestration achieved compared to landfilling.

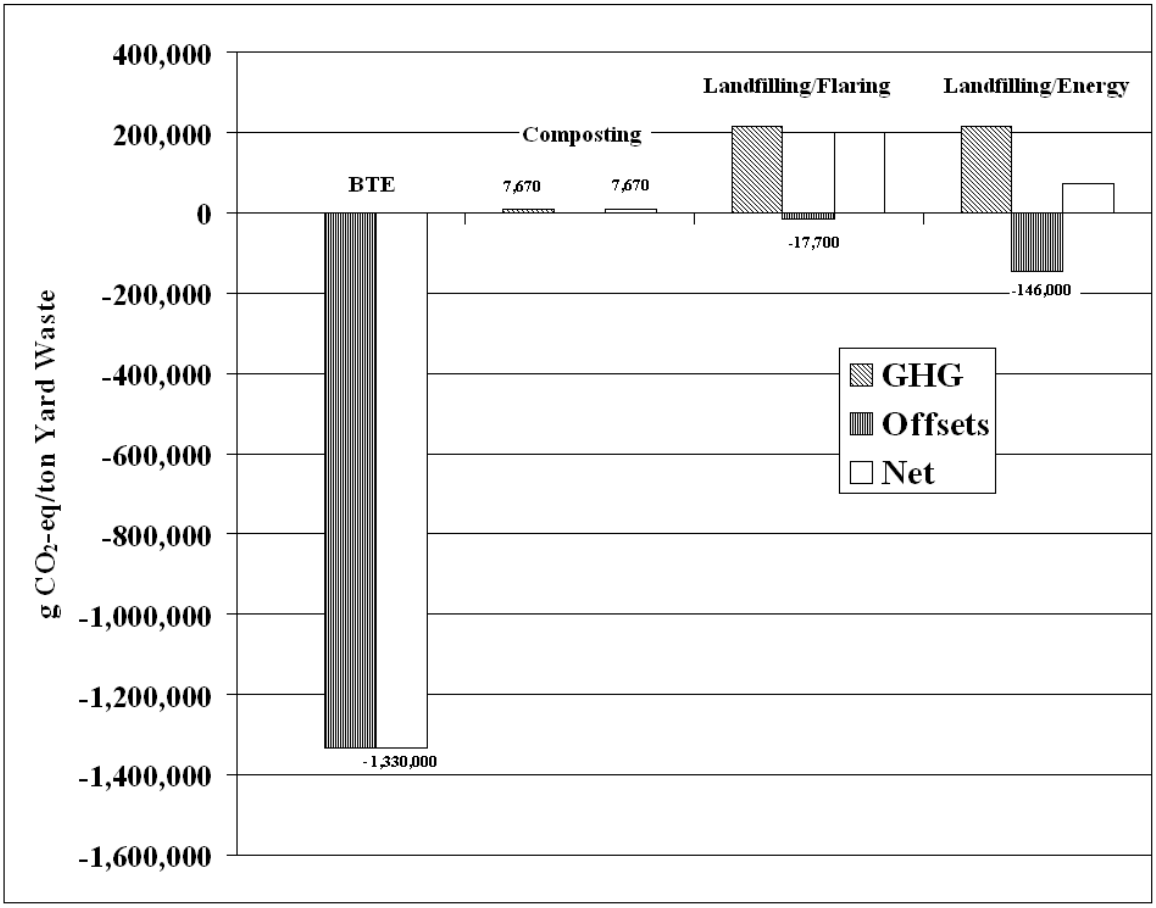


Figure 19. GHG Emissions and Offsets for the Various Management Options-Excluding Carbon Sequestration and Biogenic Emissions.

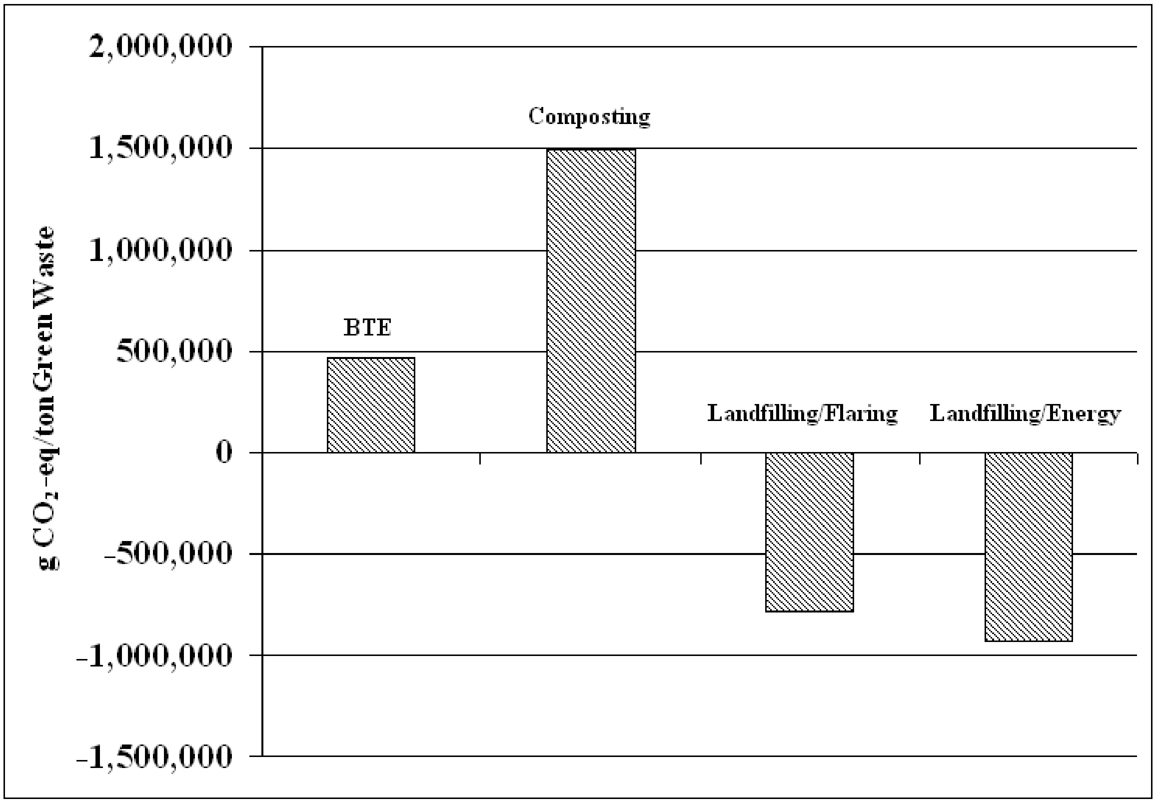


Figure 20. Net GHG Emissions-Including Carbon Sequestration and Biogenic Emissions.

It should be noted that the type of energy facility being replaced has an effect on emission offsets. Nuclear power plants have relatively low GHG emissions as compared to coal, natural gas, or oil-based power plants, therefore replacing electricity from a nuclear power plant by green waste as fuel in a BTE will save GHG emissions, while replacing it with LFG will increase the GHG emissions on a per kW-hr basis.

LFG collection efficiency effect on the net GHG emission results was also assessed and an increase in efficiency from 75% to 90% was found to decrease the GHG emissions of both ADC/Flaring and ADC/Energy by 53,000 gCO_2-eq/ton green waste. Figure 21 shows the decrease in net GHG emissions with increasing LFG collection efficiency (neglecting carbon sequestration and biogenic emissions); a net GHG emission of zero is shown to be achieved when LFG collection efficiency reaches approximately 84%. Considering carbon sequestration and biogenic emissions dramatically changes the results of the LCA. The carbon stored in landfilling indicate a stable fate of carbon that was accounted for as negative CO_2-eq emissions as opposed to the biogenic emissions of combustion that might, on the long run, be transferred to methane. It should be noted that this approach in comparative LCA resulted in conservative conclusions.

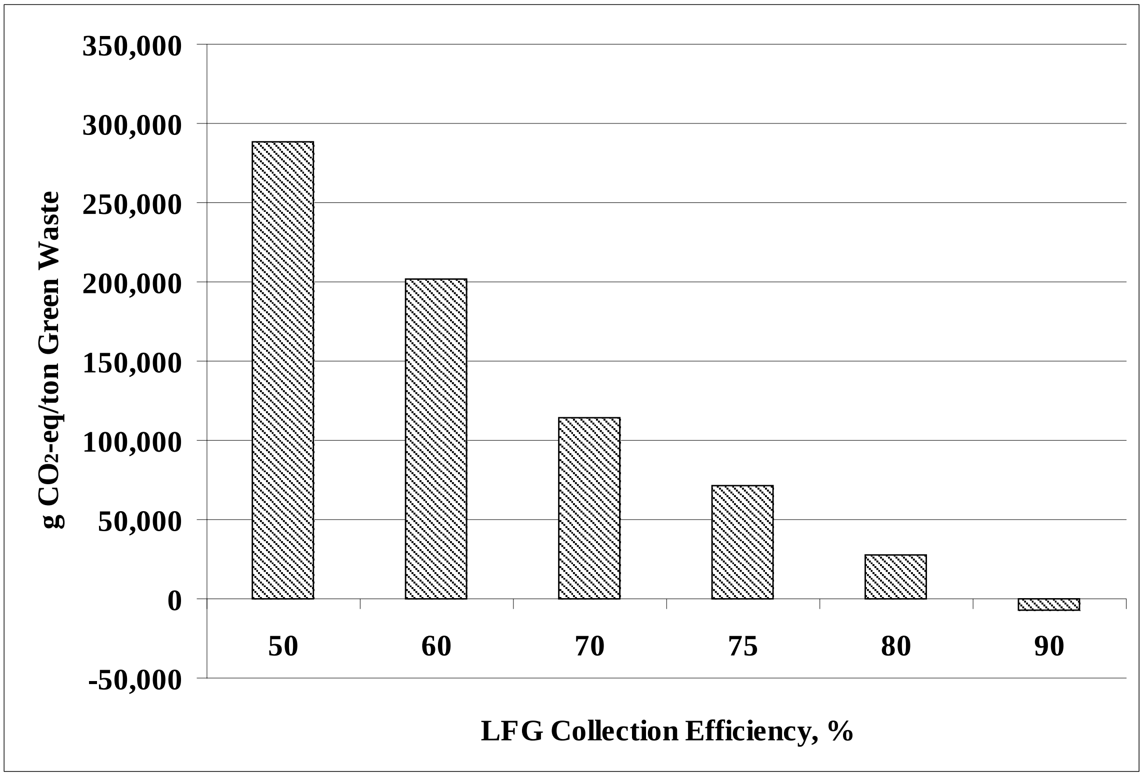


Figure 21. Landfilling/Energy Net GHG Emissions at Increasing LFG Collection Efficiency (Neglecting Carbon Sequestration).

Using mulch as daily cover instead of soil can eliminate the cost of purchasing soil; one m^3 of soil was estimated to cost \$3.7 (2009 US\$) to deliver to the landfill (EMCON 1997), while shredding the green waste in preparation for use as ADC was calculated to cost \$2.2 per m^3 (Fitzgerald, 2009). Also, the landfill volume savings possible due to the compaction and degradation of mulch covers (as much as 6% of the initial landfill volume) has an economical value related to expanding the life time of a landfill, delaying the construction of a new facility, and allowing extended time for better environmental technologies to be implemented at the new landfill.

Conclusions

Considering both carbon sequestration and biogenic emissions dramatically changes the results of the LCA. Accounting only for non-biogenic GHG emissions showed that use of mulch as biofuel actually is the best environmental practice providing exceptional GHG emission offsets, while landfilling generated positive net GHG emissions. On the other hand, when carbon sequestration and biogenic emissions are accounted for, only landfilling provided GHG emission offsets, while using mulch as biofuel generates positive net GHG emissions.

Considering only non-biogenic emissions, it was found that GHG associated with fugitive gas was relatively high compared to the other management options. However, at a LFG collection efficiency as high as 84%, zero net GHG emissions from mulch use as landfill cover with energy recovery were estimated. However, it should be noted that methane emissions were based on a conservative calculation; not considering the oxidation of methane through the mulch covers which will decrease the values of methane emissions and increase that of biogenic CO_2. It may be the case that application sites (or market outlets) do not have the capacity for all generated compost, and thus, storage issues have to be considered. Also, mulch production at a WMF could exceed the need for daily cover which again might lead to storage of excess mulch in piles promoting anaerobic degradation and odor production.

Burning mulch as fuel in a BTE facility had the highest methane emission offsets due to replacing coal as energy source in this study. However combustion releases all the carbon content in green waste as CO_2, generating positive net GHG emissions if biogenic CO_2 is considered. It should be noted that this study only focuses on GHG emissions, neglecting any other environmental impacts such as acidification, ozone depletion potential, or human health.

The use of mulch as alternative daily cover appears to be an environmentally sound option compared to both combustion and composting when carbon sequestration is considered. Also, both the volume savings gained with the use of mulch as daily cover and replacing soil makes it an economically feasible option for both green waste and landfill management in general.

References

Abichou, T., Chanton, J., Powelson, D., Fleiger, J., Escoriaza, S., Yuan, L., Stern, J. (2006). “Methane flux and oxidation at two types of intermediate landfill covers”. Waste Management 26, 1305–1312.

Aragno, M. (1988). “The landfill ecosystem: a microbiologist’s look inside a black box”. In the landfill: lecture notes in earth sciences #20, ed. P. Baccini, Springer Verlag. New York, pp. 15-38

Barlaz, M. (1997). “Biodegradative Analysis of Municipal Solid Waste in Laboratory-Scale Landfills.” U.S. Environmental Protection Agency Report #EPA 600/R-97-071, Washington, D.C.

Barlaz, M. (1998). “Carbon storage during biodegradation of municipal solid waste components in laboratory-scale landfills”. Global biogeochemical cycles. Vol. 12, No. 2. 373-380.

Barlaz, M. (2008). “Corrections to previously published carbon storage factors”. Dept. of Civil, Construction, and Environmental Engineering.

Barlaz, M., Chanton, J., Green, R. (2009). “Controls on landfill gas collection efficiency: instantaneous and lifetime performance”. Journal of the air and waste management association. 59(12):1399-404.

Barlaz, M., Green, R., Chanton, J., Goldsmith, C., Hater, G. (2004) “Evaluation of a biologically active cover for mitigation of landfill gas emissions”. Environmental Science and Technology (38), pp. 4891–4899.

Barlaz, M., Schafer, D., Ham, R. (1989) “Bacterial population development and chemical characteristics of refuse decomposition in a simulated sanitary landfill”. Appl. Environ. Microbiol., 55, 55-65.

Barlaz, M, Ham, R., Schaefer, D. (1989). “Mass-balance analysis of anaerobically decomposed refuse” J. Environ. Engin., 115, 1088-1102.

Bary, A. I., Cogger, C.G., Sullivan, D.M., Myhre, E.A. 2005. “Characterization of fresh trimmings for agricultural use”. Bioresource Technology 96 (2005) 1499-1504.

Bhander, G., Kirkeby, J., Hauschild, M., Christen-sen, T. (2006). “Life cycle assessment models for solid waste managements systems – A review”. Non-published article. Institute of Environment and Resources, technical University of Denmark, Kgs. Lyngby, Denmark.

Cabaraban, M., Khire, M., Alocilja, E. (2008). “Aerobic in-vessel composting versus bioreactor landfilling using life cycle inventory models”. Clean Techn Environ Policy 10:39–52.

California Integrated Waste Management Board (CIWMB). (2009). “Alternative daily cover white paper”. Unpublished results.

Chaya, W., Gheewala, S. (2006). “Life cycle assessment of MSW-to-energy schemes in Thailand”. 2006 Elsevier Ltd.

Cherubinia, F., Birda, N., Cowieb, A., Jungmeiera, G., Bernhard Schlamadingerc, Woess-Gallascha, S. (2009). “Energy- and greenhouse gas-based LCA of biofuel and bioenergy systems: Key issues, ranges and recommendations” Resources, Conservation and Recycling (53), 434–447.

Code of Federal Regulations - Title 40: Protection of Environment. December 2005.

Cogger, C., Bary, A., Sullivan, D. (2002). “Fertilizing with yard trimmings”. Washington State University.

Cummings, S., Stewart, C. (1994). “Newspaper as a substrate for cellulolytic landfill bacteria”. J. Appl. Bacteriol., 76, 196-202.

Department of Energy (DOE) (1999). “Carbon Sequestration Research and Development-a Report by DOE's Office of Fossil Energy and Office of Science”.

Eggleston, S., Buendia, L., Miwa, K., Ngara, T., Tanabe, K. (2006). “Biological Treatment of Solid Waste. Guidelines for National Greenhouse Gas Inventory”. Intergovernmental Panel on Climate Change, IPCC, 2006.

European Commission (2009). “Europe 2020: A European strategy for smart, sustainable and inclusive growth”.

Environmental Research and Education Foundation. (1998). “Final Report on the Life-Cycle Inventory of a Modern Municipal Solid Waste Landfill”. Prepared by Ecobalance.

Finnveden G., Johansson J., Lind P., Moberg A. (2004). “Life Cycle Assessments of Energy from Solid Waste”. Journal of Cleaner Production. 13(3):231-240.

Fitzgerald, G. (2009). “Technical and Economic Analysis of Pre-shredding Municipal Solid Wastes Prior to Disposal”. MS Thesis, Columbia University, Unpublished Results.

Haaren, R.V. (2009). “Large scale aerobic composting of sourceseparated organic wastes: A comparative study of environmental impacts, costs, and contextual effects”. Master thesis from University of Columbia.

Haaren, R., Themelis, N., Barlaz, M. (2010). “LCA comparison of windrow composting of yard wastes with use as alternative daily cover (ADC)” Waste Management. Dec;30(12):2649-56.

Haight, M. (2005). “Assessing the environmental burdens of anaerobic digestion in comparison to alternative options for managing the biodegradable fraction of municipal solid wastes”. Water Science & Technology Vol 52 No 1-2 pp 553–559.

Ham, R., Fritschel, P., Norman, M. (1993) “Refuse decomposition at a alarge landfill”. Proceedings Sardina 93, Fourth international landfill symposium, Cagliari, Italy: CISA, Environmental sanitary engineering centre. Pp. 1046-1054.

Harrison, W.K., Dumas, R.D., Barlaz, A.M. 2000. “A Life-Cycle Inventory Model of Municipal Solid Waste Combustion”. Journal of the Air & Waste Management Association, Volume 50.

Haughey, R.D. Landfill alternative daily cover: conserving airspace and reducing landfill operating cost, J. Waste Manag. Res. **19** (2001), pp. 89–95.

Hellebrand, H., Kalk, W. (2001). “Emission of methane, nitrous oxide, and ammonia from dung windrows”. Nutrient Cycling in Agroecosystems 60:83–87.

Hilger, H., Humer, M. (2003). “Biotic landfill cover treatments for mitigating methane emissions”. Environmental Monitoring and Assessment (84), pp. 71–84.

Hoogwijk, M., Faaij, A., Broek, R., Berndes, G., Gielen, D. (2003). “Exploration of the ranges of the global potential of biomass for energy”. Biomass Bioenergy 25(2):119–33.

Humer, M., Lechner, P. (1999). “Alternative approach to the elimination of greenhouse gases from old landfills”. Waste Management and Research (17) pp. 443–452.

Intergovernmental Panel on Climate Change (IPCC). (2010) “Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories”. National Greenhouse Gas Inventories Programme, Montreal, IPCCXVI/ Doc. 10 (1.IV.2000), May 2000.

International Energy Agency (2008). “United States renewable energy market report”.

Kaplan, O., Decarolis, J., Thorneloe, S. (2009). “Is it better to burn or bury waste for clean electricity generation?”. Environmental science and technology 43, 1711–1717.

Kaplan P. O., Ranjithan S. R., Barlaz M. A. (2008). “Use of Life-Cycle Analysis to Support Soil Waste Management Planning for Delware”. Environmental Science & Technology.

Kaufman S., Themelis, N. (2009). “Using a direct method to characterize and measure flows of municipal solid waste in the United States”. J. Air Waste Manag. Assoc. (59), pp. 1386–1390.

Khan, A. (1977). “Anaerobic degradation of cellulose by mixed culture”. Can. J. Microbiol., 23, 1700-1705.

Kirkeby, J. T., Birgisdottir, H., Hansen, T. L., Christensen, T. H. (2005). “Evaluation of environmental impacts from municipal solid waste management in the municipality of Aarhus, Denmark (EASEWASTE)”. Waste Management & Research, 24, 16-26.

Komilis, D., Ham, R. (2004). “Life-cycle inventory of municipal solid waste and yard waste windrow composting in the United States”. Journal of Environmental Engineering 130 (11)1390–1400.

Komilis, D., Ham, R. Park, J. (2003). “Emission of volatile organic compounds during composting of municipal solid wastes”. Water Resources 38:1707–1714.

National Council for Air and Stream Improvement (NCASI), http://www.ncasi.org.

National Regulatory Research Institute (2008). “What Generation Mix Suits Your State? Tools for Comparing Fourteen Technologies Across Nine Criteria”.

Pagans, E., Font, X., Sanchéz, A. (2006). “Emission of volatile organic compounds from composting of different solid wastes: abatement by biofiltration”. Journal of Hazardous Materials B131:179–186.

Pfeffer, J., Khan, A. (1976). “Microbial production of methane from municipal refuse” Biotechnol. Bioeng., 18, 1179-1191.

Ragobnig, A., Wartha, C. (2008). “Energy efficiency in waste-to-energy and its relevance with regard to climate control”. Waste Management & Research 26: 70–77.

Rhyner, C., Schwarts, L., Wenger, R., Kohrell, M. (1995). “Waste Management and Resource recovery”. CRC Press LLC.

Robinson, D. (1986). “The Solid waste handbook: a practical guide”. Wiley-Interscience.

Samir K. Khanal, S., Surampalli, R., Zhang, T., Lamsal, B., Tyagi, R., Kao, C. (2010). “Bioenergy and Biofuel from Biowastes and Biomass”. ASCE Publications, Technology & Engineering.

Schu, R. (2007) “Burning waste efficiently”. Umweltmagazin 4–5.

Smith, A., Brown, K., Ogilvie, S., Rushton, K., Bates, J. (2001) “Waste Management Options and Climate Change-Final report to the European Commission”. DG Environment, Brussels, Belgium.

Solano, E., Dumas, R. D., Harrison, K. W., Ranjithan, S. R., Barlaz, A. M., & Brill, E. D. 2002. “Life-cycle-based solid waste management. II Illustrative applications”. Journal of Environmental Engineering, 128(10), 93-1005.

Stephens, (2007). ’Innovations’ Case Studies: Organics Options.

Stern, J.C., Chanton, J., Abichou, T., Powelson, D., Yuan, L., Escoriza, S., Bogner, J. (2007). “Use of a biologically active cover to reduce landfill methane emissions and enhance methane oxidation”. Waste Management 27 (9), 1248–1258.

Suflita, J., Gerba, C., Ham, R., Palmisano, A., Rathje, W., Robinson, J. (1992). “The world’s largest landfill”. Environ. Sci., Technol., 26, 1486-1495.

Sydney: NSW Department of Environment and Conservation and Recycled Organics Unit, The University of New South Wales. (2007). “Recycled Organics Unit. Greenhouse gas emissions from composting facilities: second edition”.

Taylor, C., Kashmanian, R. (1988). “Study and assessment of eight yard waste composting programs across the United States, EPA/530-SW-89-038.

Tchobanoglous, G., Theisen, H., Vigil, S. (1993). “Integrated Solid Waste Management: Engineering Principles and Management Issues”. McGraw Hill, Inc., USA.

The State Of Garbage In America. BioCycle December 2008, Vol. 49, No. 12, p. 22.

Thorneloe, S., Weitz, K., Nishtala, S., Yarkosky, S., Zannes, M. (2002). “The impact of municipal solid waste management on greenhouse gas emissions in the United States”. Journal of the Air & Waste Management Association, 52, pp. 1000-1011.

Thorneloe, S., Weitz, K., Jambeck, J. (2005). “Moving from solid waste disposal to materials management in the United States”. Proceedings of the Sardinia ‘05, International Solid and Hazardous Waste Symposium, published by CISA, University of Cagliari, Sardinia.

Uhlar-Heffner, G., Reed, B., Jackson, S. 1998. “Dealing with yard trimmings in the Puget Sound”. Biocycle 30 (5), 32–36.

U. S. Department of Energy, Energy Efficiency and Renewable Energy Clearinghouse, Biomass Cofiring: A Renewable Alternative for Utilities.

U. S. Environmental Protection Agency/Office of Solid Waste (2008). “Municipal Solid Waste in the United States: 2008 Facts and Figures”.

U. S. Environmental Protection Agency (2006). “Solid Waste Management and Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks”.

U. S. Environmental Protection Agency (2002). “Solid waste management and greenhouse gases: a life-cycle assessment of emissions and sinks”. Washington, DC: US Environmental Protection Agency; p. 77–78.

U. S. Environmental Protection Agency (2010). “Inventory of US greenhouse gas emissions gas emissions and sinks 1990-2008”.

U. S. Environmental Protection Agency. (1991). “Nonroad Engine and Vehicle Emission Study”. Appendixes, (ANR-443), 21A-2001, Office of Air and Radiation.

U. S. Environmental Protection Agency. (1998). “AP-42 emission factors for municipal solid waste landfills—Supplement E, November 1998”.

U. S. Environmental Protection Agency. (1994). “Composting yard trimmings and municipal solid wastes”. EPA, 530-R-94-003, May.

U. S. Environmental Protection Agency (2001). “Determination of financial assurance for landfills”. Publication 777

Wandschneider, J., Seiler, U., Hölter, G., Wilmann, T. (2005). “Increase of the electrical energy efficiency to 30% due to a high performance boiler – example of HR-AVI-Amsterdam”. Optimization in Thermal Waste Treatment. Neuruppin, Germany.

Wang, Y., Byrd, C., Barlaz, M. (1994). “Anaerobic biodegradability of cellulose and hemicellulose in excavated refuse samples using a biochemical methane potential assay”. Journal Industrial microbial., 13, 147-153.

WRAP (2006) “Environmental benefits of recycling, an international review of life cycle comparisons for key materials in the UK recycling sector”. Waste and Resources Action Program, Peer reviewed report prepared by H. Wenzel et al., Danish Technical University, published by WRAP, Banbury, Oxfordshire, England.

Young, L., Frazer, A. (1987). “The fate of lignin and lignin derived compounds in anaerobic environments”. Geomicrobiology J., 5, 261-293.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Management of yard waste is a significant challenge in the US, where, in 2008, yard waste was reported to be 13.2% of the 250 million tons of municipal solid waste (MSW) (USEPA, 2008). Because of its volume and potential use as a soil amendment, the disposal of yard waste in lined landfills is banned in most states. Use of mulch as landfill cover provides an outlet for handling high green waste volumes. However, the efficiency of mulch covers as daily and intermediate landfill covers have never been assessed before. This study provided an extensive and comprehensive analysis of the properties and characteristics of vegetative mulch through geotechnical testing.

To account for the greater particles size of mulch as opposed to soil, geotechnical tests have been adjusted in the laboratory, i.e. a larger shear box was made and used in the shear strength testing, and a new approach to consolidation testing was followed. The behavior of mulch was monitored (side by side with more conventional cover material, i.e. soil and soil/mulch mixture covers) when functioning as landfill covers through field testing. Also, an accurate calculation of landfill volume reduction, that takes into consideration the geometry of the landfill and the characteristics of cover material, was provided through creating a model that divides the landfill volume into small units that change in volume according to the coordination and the type of material of each unit.

It was found in this study that the angularity and size of mulch particles result in the high porosity (71%) that characterized the behavior of fresh mulch as a landfill cover, i.e., relatively high hydraulic conductivity (0.12 cm/sec), high shear strength (friction angle = 16^0), and low dry bulk unit weight ($2.7 kN/m^3$). Therefore, mulch covers are expected to act poorly in controlling infiltration, generating greater amounts of leachate in landfills than soil covers. As a matter of fact, both hydraulic modeling and field water balance monitoring showed greater control of infiltration into the landfill for soil and soil/mulch mixture covers than mulch covers due to the higher hydraulic conductivity of mulch. However mulch is expected to increase in the ability to prevent water from infiltrating into the landfill with time as degradation occurs and porosity decreases.

Use of mulch covers are expected to lead to recovery of as much as 5% of the original volume of the landfill due to compaction under vertical stress. Additional volume reduction of mulch layers is expected to occur as a result of the biological degradation of the organic fractions. In the field tests, mulch cover lost 8% of its original volume due to biological degradation. This would increase the total landfill space recovery to 6% of its original volume. The significant volume reduction because of the compaction and degradation of mulch covers has an economical value in terms of expanding the life time of a landfill preventing the construction of a new facility, and also, allowing extended time for better environmental technologies to be implemented in the new landfill, potentially enhancing its performance and reducing the environmental impacts.

Mulch high porosity also promotes better aeration which was evident in the greater capacity for VOC oxidation in the field tests for mulch covers than for soil or soil/mulch mixture covers. Percent VOC removal in mulch layers was found to decline with increase in loading; suggesting nonlinear Monod-like kinetics. However there were not enough removal data points to identify the point of oxidation saturation (or maximum removal capacity). Daily cover is not expected to provide VOC control because of the 200-day lag period observed in the field.

Mixed covers had soil-like behavior in terms of both VOC oxidation and infiltration control. It is possible that depending on the desired function of the cover, soil/mulch mixture covers can be prepared at different mixing ratios. In this study, HELP model was found to simulate actual infiltration through mix covers to an acceptable degree of accuracy. Thus, HELP model is suggested to be used in designing mulch/soil mixture covers with optimum behavior.

Considering both carbon sequestration and biogenic emissions dramatically changes the results of the LCA. Accounting only for non-biogenic GHG emissions showed that use of mulch as biofuel actually is the best environmental practice providing exceptional GHG emission offsets, while landfilling generated positive net GHG emissions. On the other hand, when carbon sequestration and biogenic emissions are accounted for, only landfilling provided GHG emission offsets, while using mulch as biofuel generates positive net GHG emissions.

Table 14 presents risk assessment of the use of vegetative mulch as an alternative daily cover. The various functions and benefits of a daily cover were classified as “low” or “high” according to their environmental and economical impact. Mulch covers were found to function poorly as a hydraulic barrier, which was considered to have a low impact on leachate generation rates since only daily covers are considered. The table shows that the use of mulch as daily cover will have a high beneficial impact mainly because of both the volume savings and the economic feasibility of replacing soil.

Table 14. Risk Assessment of the Use of Mulch as Daily Cover

<table>
<tr><td colspan="2" rowspan="2"></td><td colspan="2">Efficiency</td></tr>
<tr><td>Low</td><td>High</td></tr>
<tr><td rowspan="4">Benefit</td><td rowspan="2">Low</td><td>Infiltration control</td><td>VOC control</td></tr>
<tr><td></td><td>Carbon sequestration</td></tr>
<tr><td rowspan="2">High</td><td></td><td>Volume reduction</td></tr>
<tr><td></td><td>Economic feasibility</td></tr>
</table>

Recommendations

This study provides a significant step towards complete understanding of behavior of vegetative mulch covers in landfills. However, a variety of environmental and economical issues need to be addressed and taken into consideration to better understand the results of this study:

- An economic study that analyzes the different management processes for green waste; including the costs of construction, operation and maintenance of a biofuel to energy-facility, composting facility, and landfill will indicate the feasibility of the various management options.

- Investigating the water quality of both infiltrating precipitation through and runoff over the studied covers to assess any additional environmental impacts related to use of mulch covers and compare that to the more conventional soil covers.
- Investigating GHG emission offsets for use of compost as a soil amendment and fertilizer, since the offsets have been continuously qualitatively accounted for in literature with no quantitative analysis. It is believed that offsets related to composting could affect the conclusions drawn in this and previous LCAs.
- Testing cover removal efficiency at controlled methane loading for extended periods of time to be able to define the full removal capacity (saturation) of mulch covers, and to assess the behavior of bio-covers that has been proposed to follow Monod type kinetics.

APPENDIX A: QUAILTY CONTROL AND QUALITY ASSURANCE (QA/QC)

A quality assurance and quality control (QA/QC) plan was followed in order to ensure the reliability of the results, as well as to minimize errors while collecting and analyzing the samples. The activities used for sampling and analyzing the tested material in the laboratory and field are discussed below.

Drying containers

Glassware, evaporation dishes, and sieves were triple washed and dried using a dry paper towel for one minute before weighing them.

Sample Collection

Mulch is commonly stored in piles; therefore samples were collected from both the surface and one-meter deep into the pile and then were mixed following recommendations for sampling solid waste (provided in ASTM 523 1-92) that account for heterogeneity.

Storage and preservation procedures

Mulch samples were stored in a walk-in refrigerator at a temperature of 5 C^0 to significantly slow down biological degradation to of the samples which might alter the particles size.

Sample Analysis

Laboratory testing and field monitoring followed minimum quality assurance and quality control requirements to assess precision and accuracy of the method used. Flux readings were taken in duplicate over 15 and 60-cm cover depths to assess the effect of cover depth on VOC removal. Two rain gauges and two evaporation pans were used to provide duplicate measurements for precipitation depth and evaporation. With the exception of particles size distribution and deformation tests, all analysis was conducted in duplicate.

Instruments Calibration

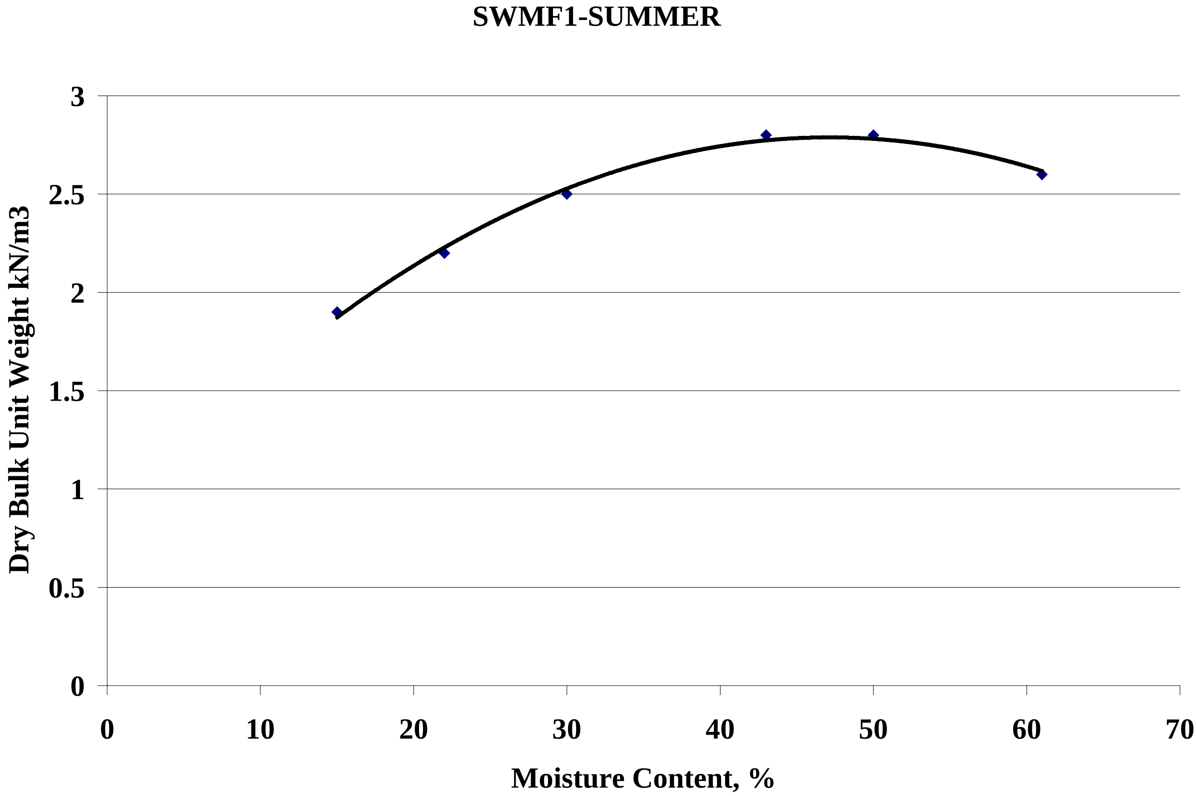
A portable MicroFID from Photovac Inc. (Waltham, Massachusetts, US) was used to measure the concentration of VOCs onsite. The MicroFID uses hydrogen and the necessary oxygen from the sample air to support combustion in the hydrogen-fed flame. MicroFID must be calibrated in order to display concentration in ppm units equivalent to the calibration gas. First a supply of zero air, which contains no ionizable gases or vapors, is used to set MicroFID's zero point. Zero air readings were always taken in an office room in Univesirt of Central Florida. Calibration gas, containing a known concentration of an 21 ionizable gas or vapor, was then used to set the sensitivity. Calibration was carried out every two weeks.

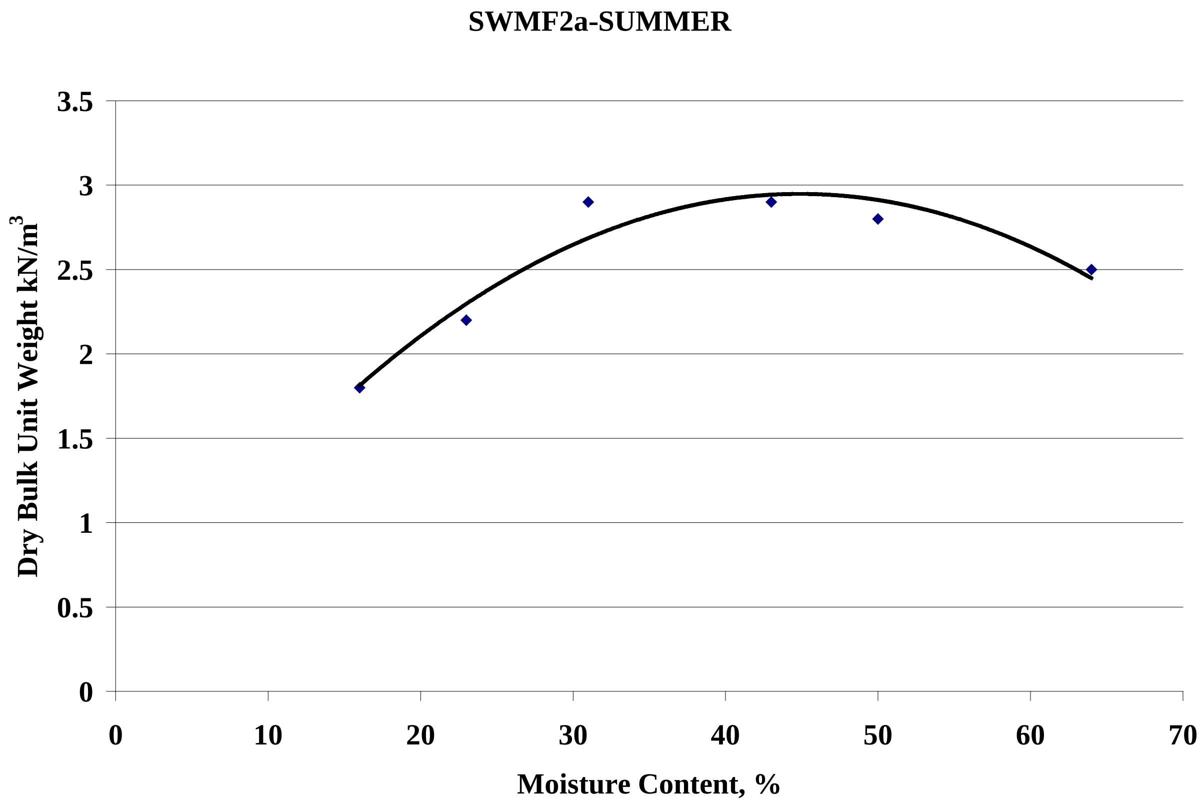
Use of Peer Reviewed Models

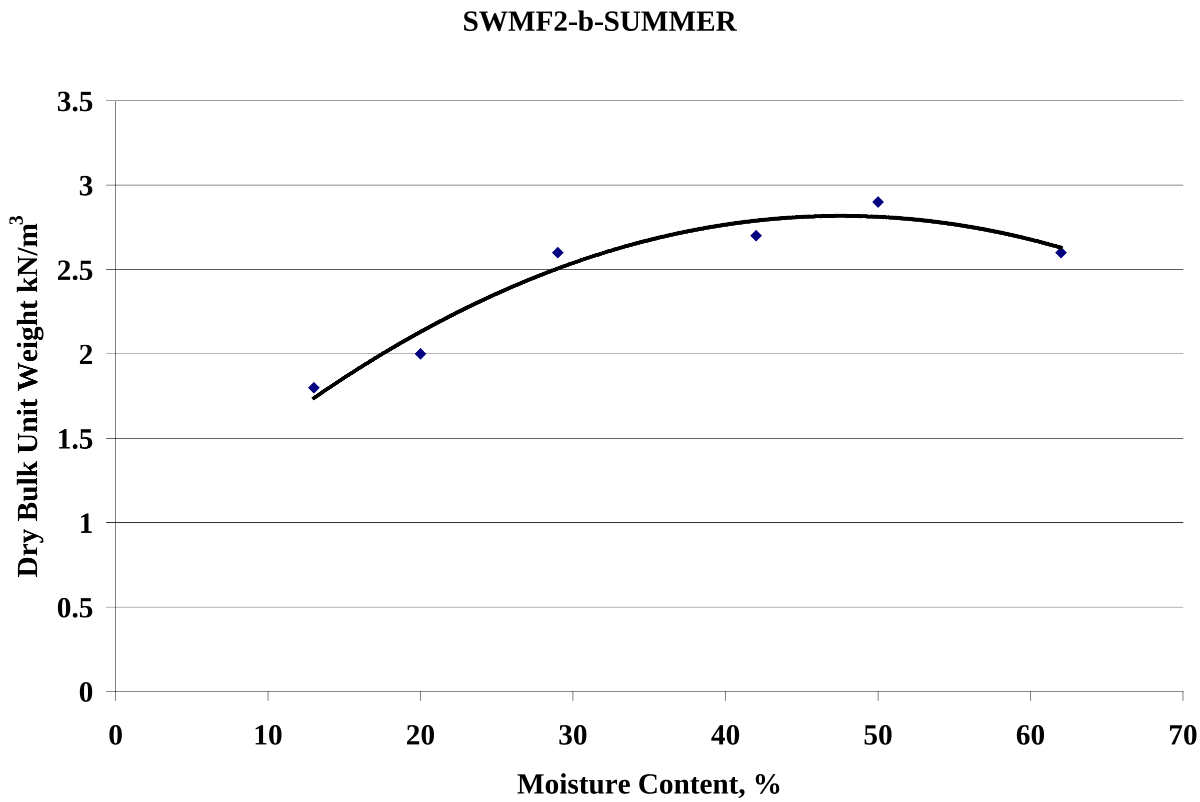
Slope/W model has been widely used to assess the stability of various landfill geometries (Jones and Dixon 2004), and the results from these analyses have been compared to those obtained from numerical analyses. HELP model is the most widely used predictive water balance landfill infiltration model (Schroeder et al. 1994). It was developed to facilitate rapid, economical estimation of the amount of surface runoff, surface drainage, and leachate that may be expected to result from the operation of a variety of possible landfill designs.

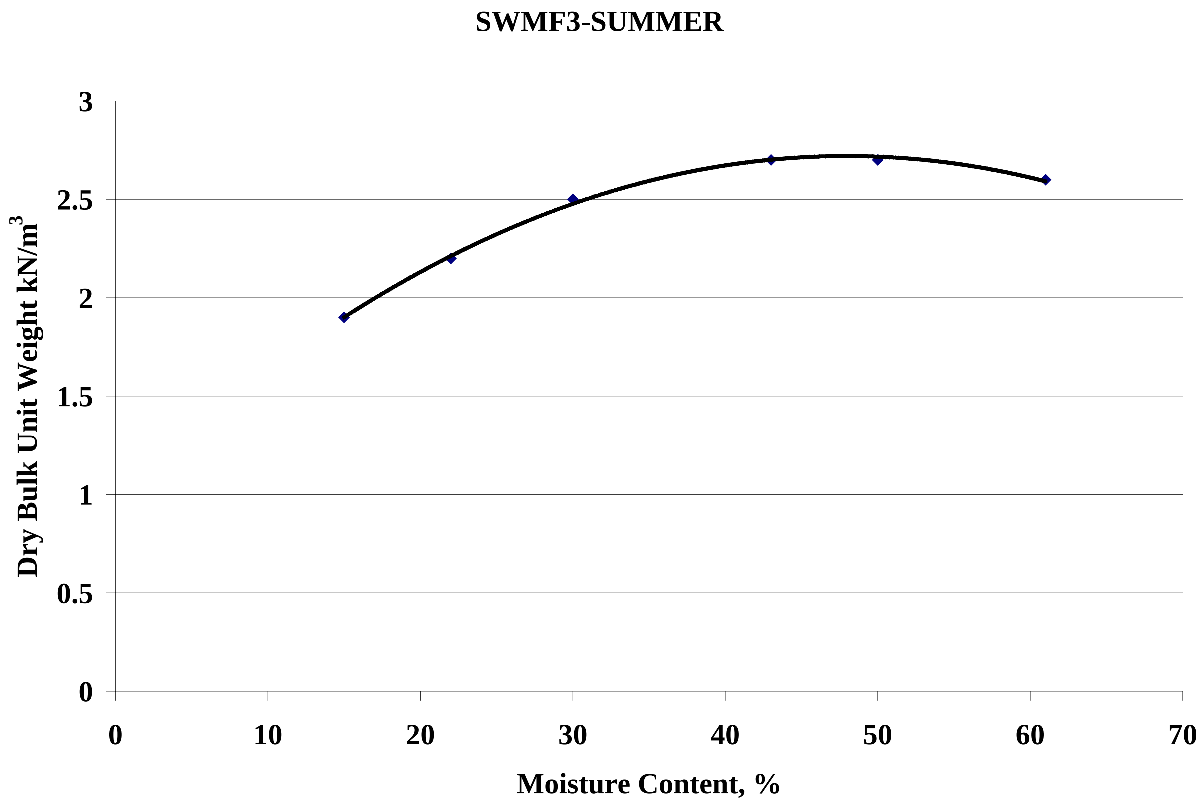
APPENDIX B: OPTIMUM MOISTURE CONTENT

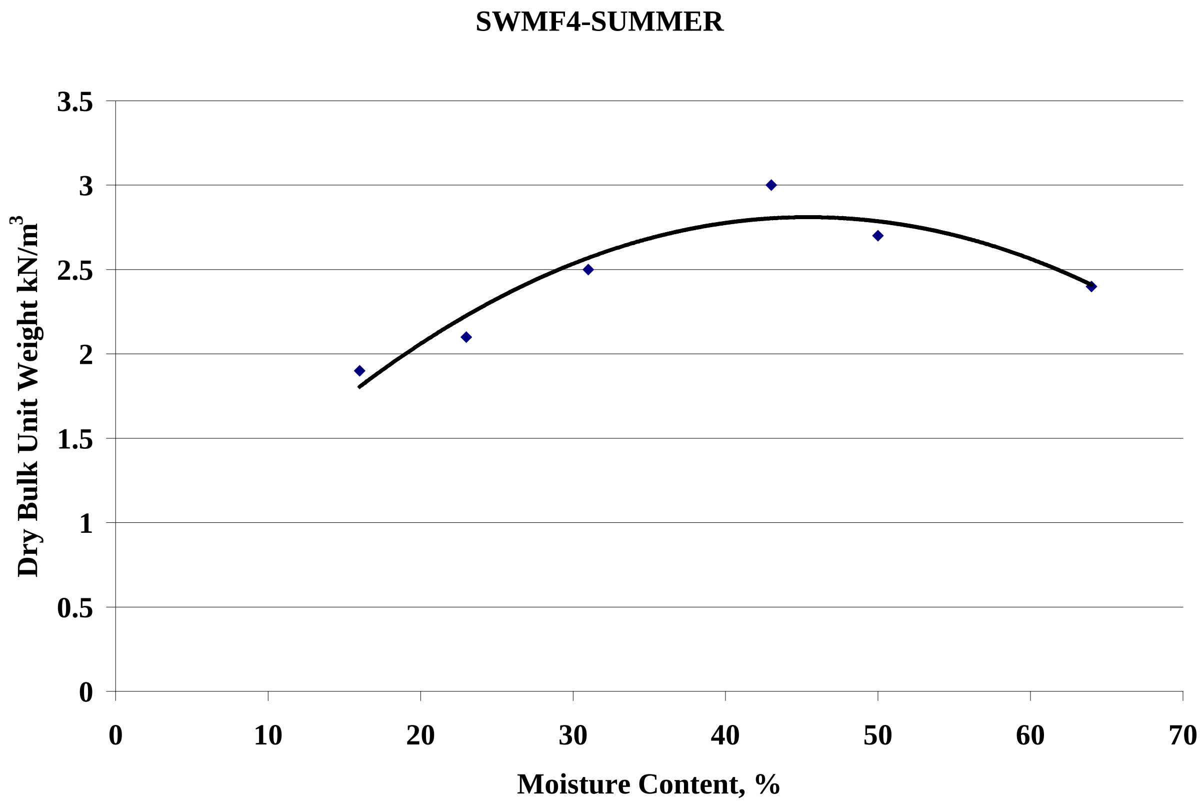
<u>Fresh Mulch (Summer)</u>

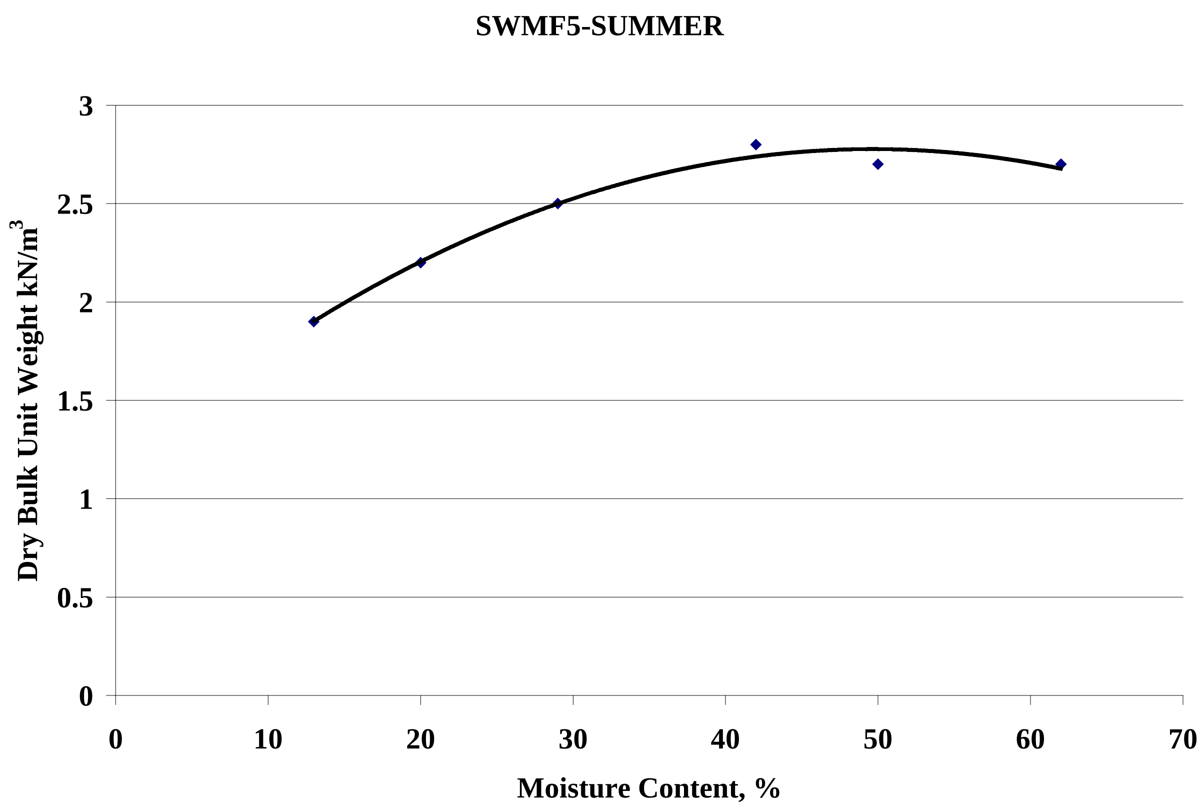



SWMF2a-SUMMER
3.5
3
2.5
2
1.5
1
0.5
0
Dry Bulk Unit Weight kN/m3
0
10
20
30
40
50
60
70
Moisture Content, %

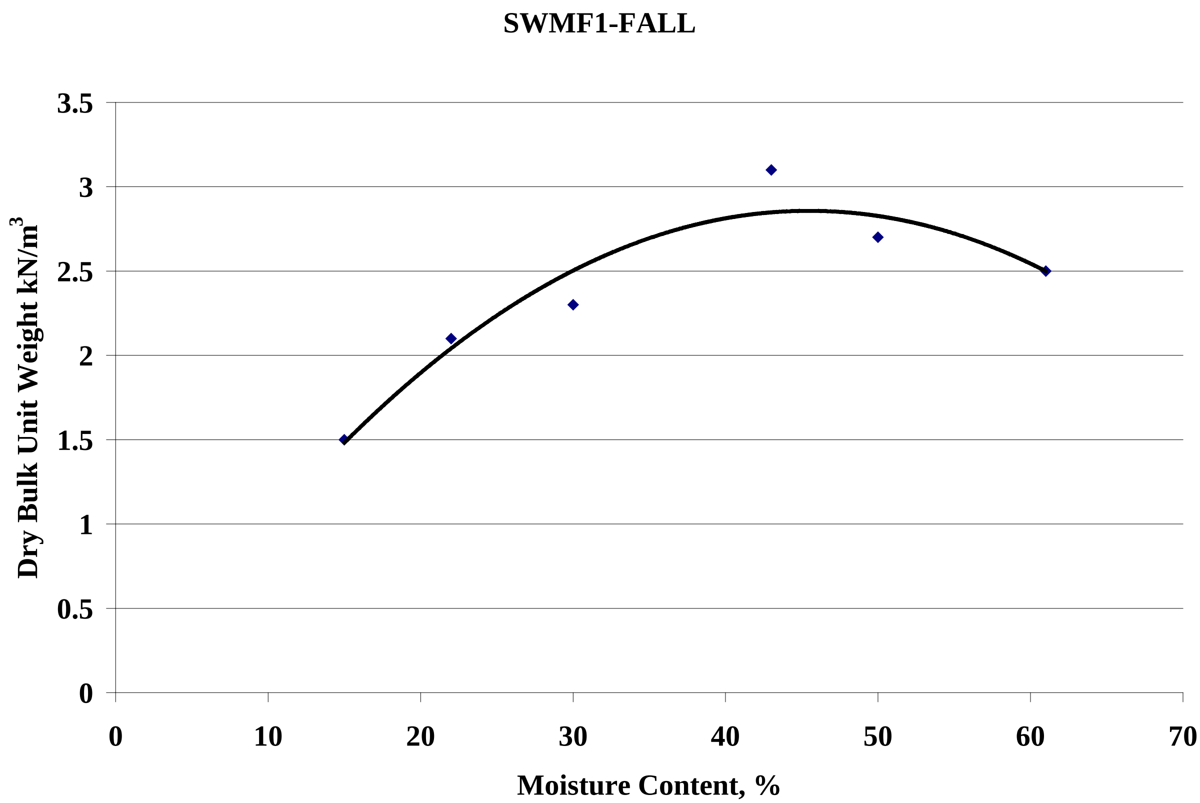

SWMF2-b-SUMMER
Dry Bulk Unit Weight kN/m3
3.5
3
2.5
2
1.5
1
0.5
0
0
10
20
30
40
50
60
70
Moisture Content, %

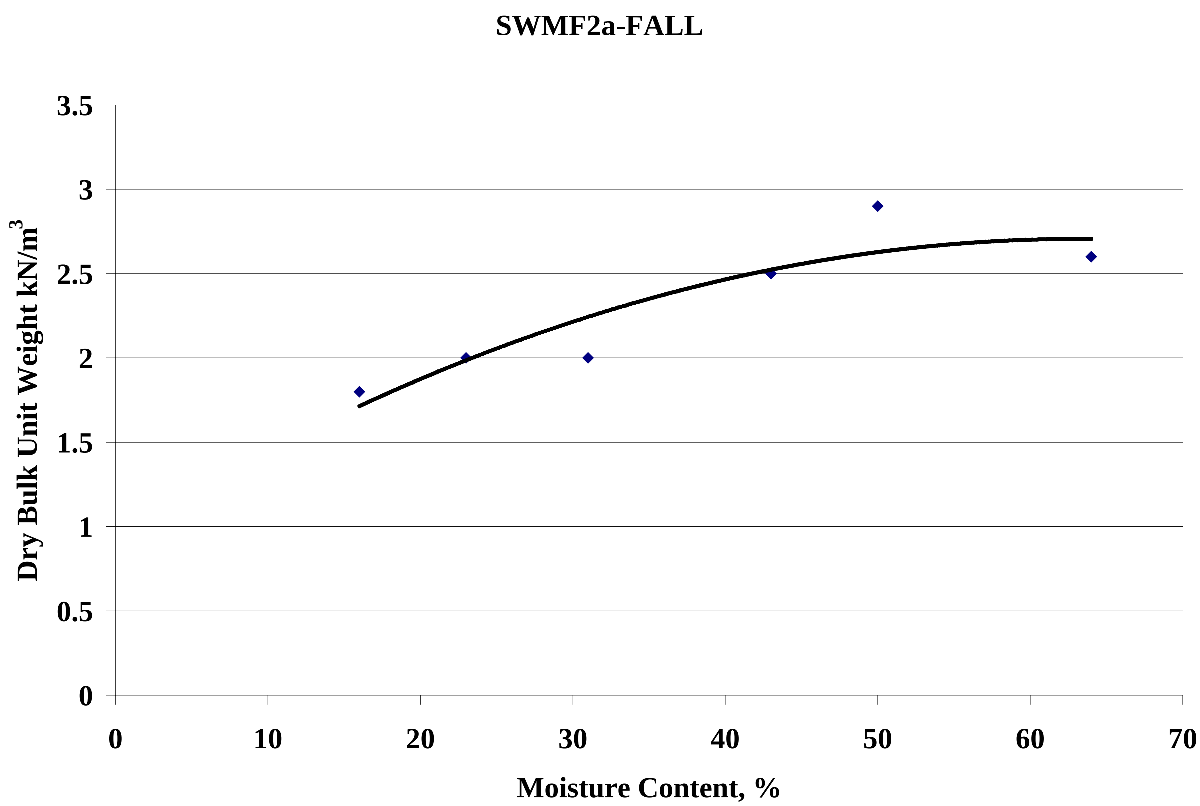

SWMF3-SUMMER
3
2.5
2
1.5
1
0.5
0
Dry Bulk Unit Weight kN/m3
0
10
20
30
40
50
60
70
Moisture Content, %

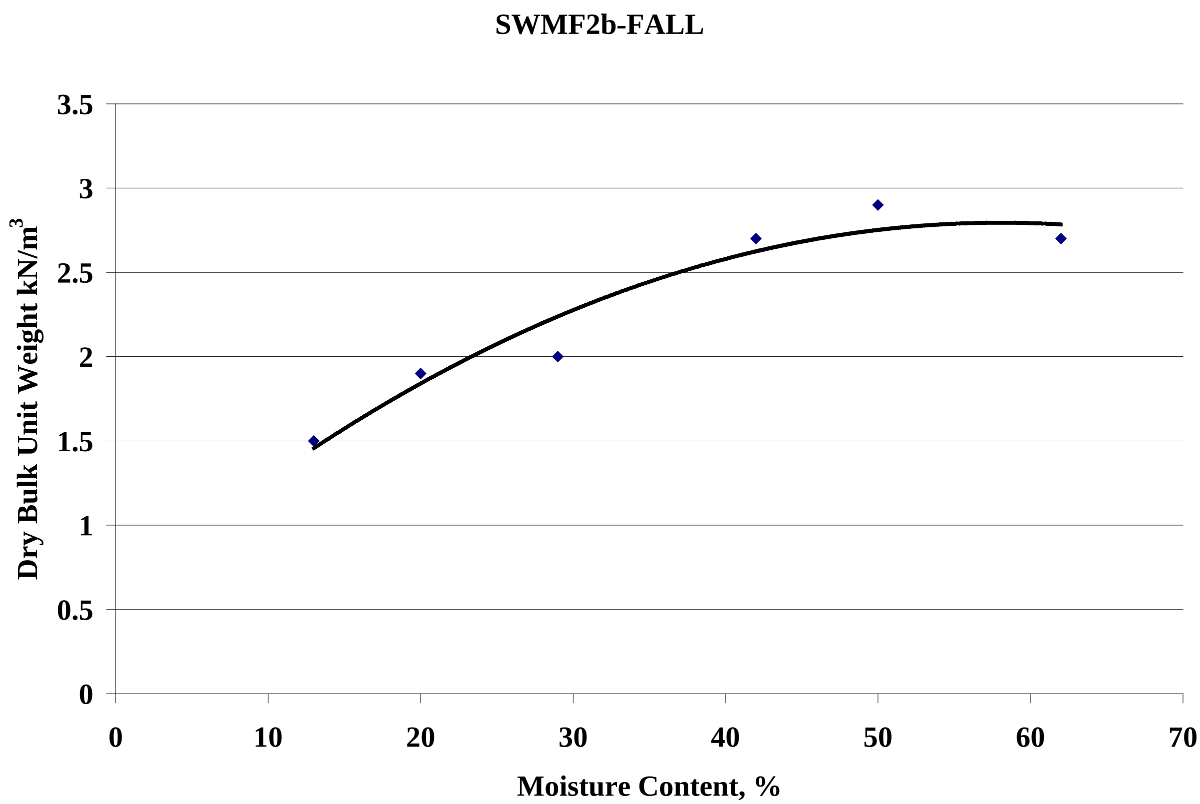

SWMF4-SUMMER
Dry Bulk Unit Weight kN/m3
Moisture Content, %
3.5
3
2.5
2
1.5
1
0.5
0
0
10
20
30
40
50
60
70


SWMF5-SUMMER
Dry Bulk Unit Weight kN/m3
Moisture Content, %
0
0.5
1
1.5
2
2.5
3
0
10
20
30
40
50
60
70

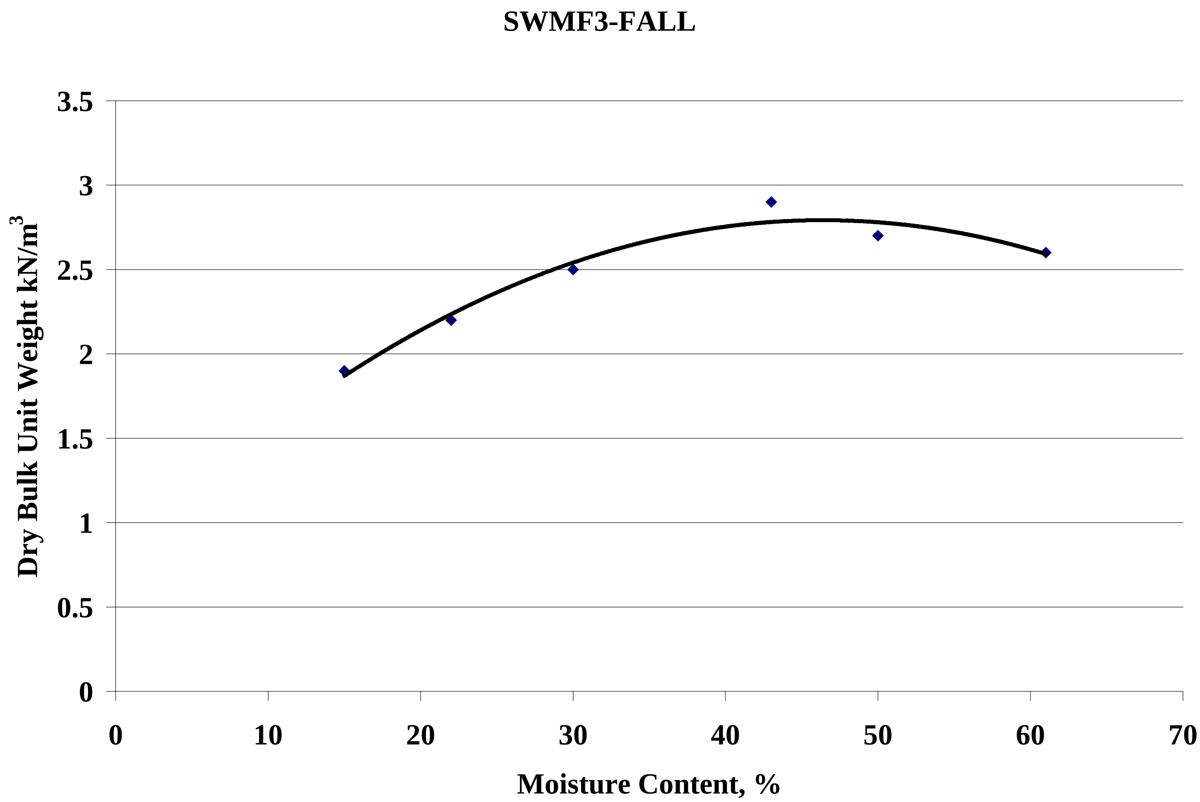
Fresh Mulch (Fall)

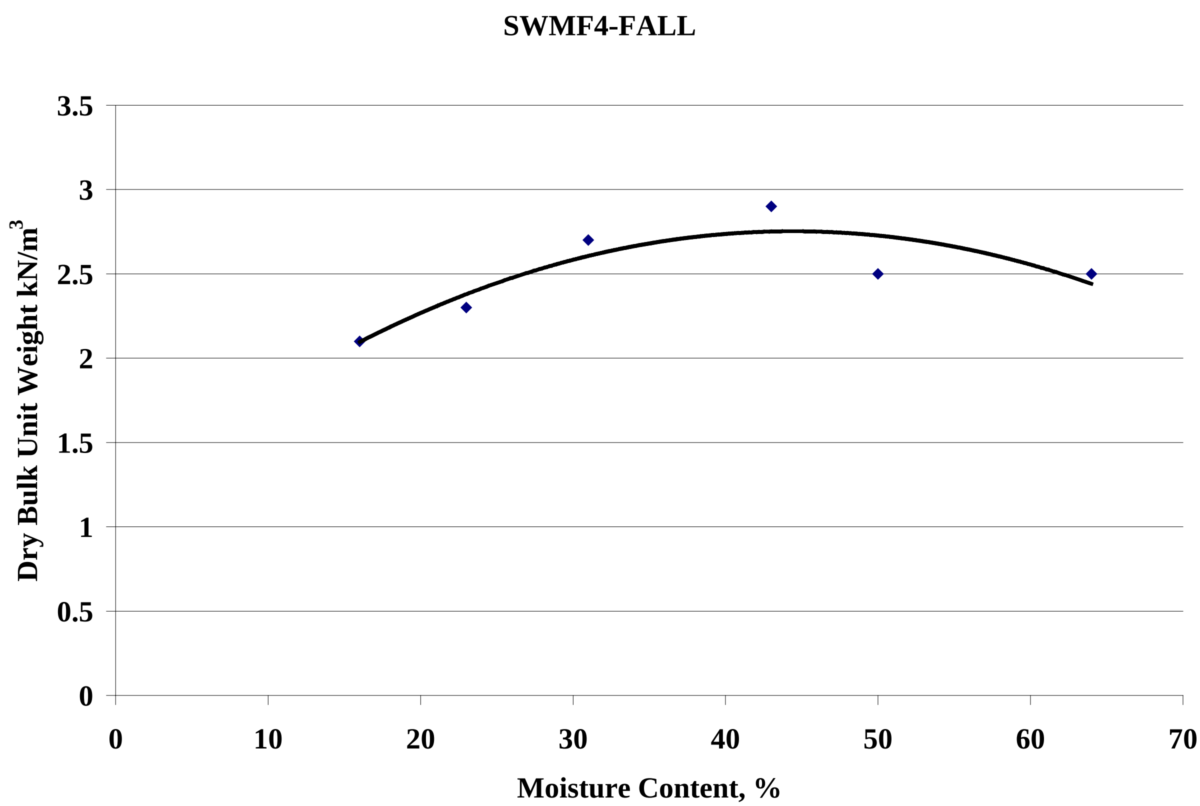


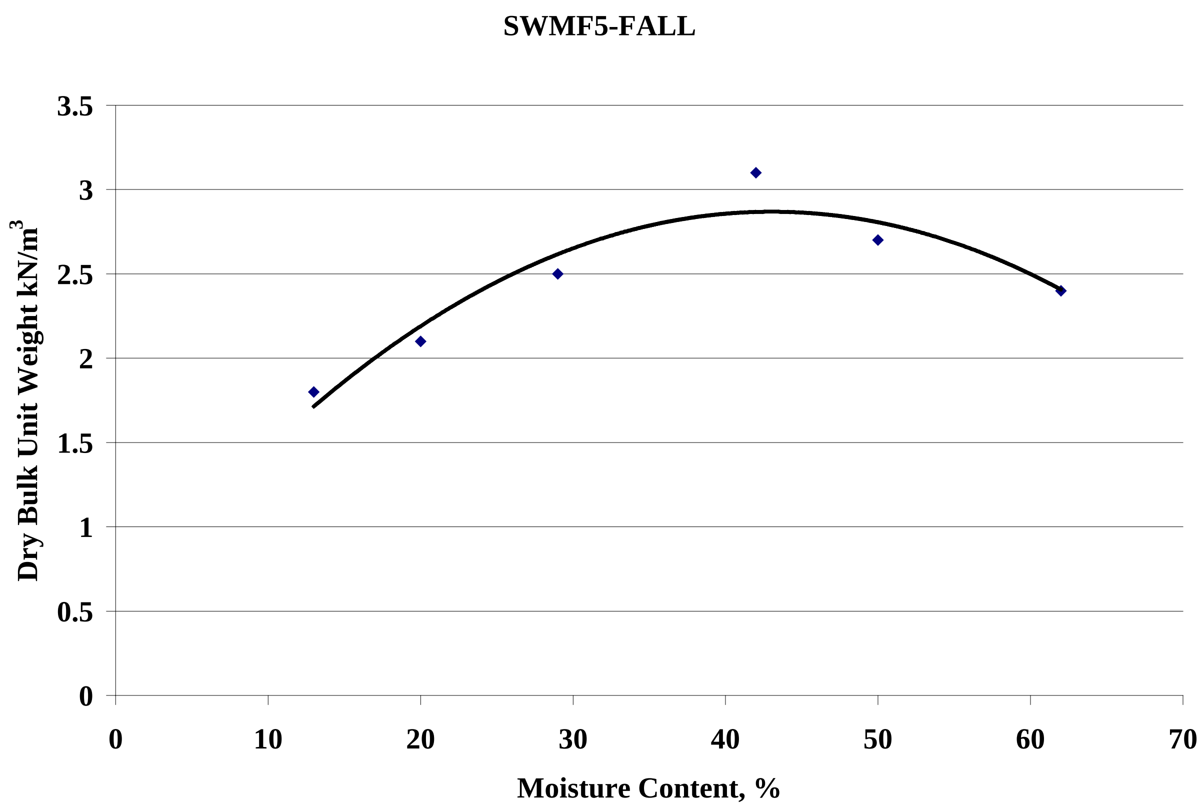

SWMF2a-FALL
Dry Bulk Unit Weight kN/m3
Moisture Content, %
0
0.5
1
1.5
2
2.5
3
3.5
0
10
20
30
40
50
60
70



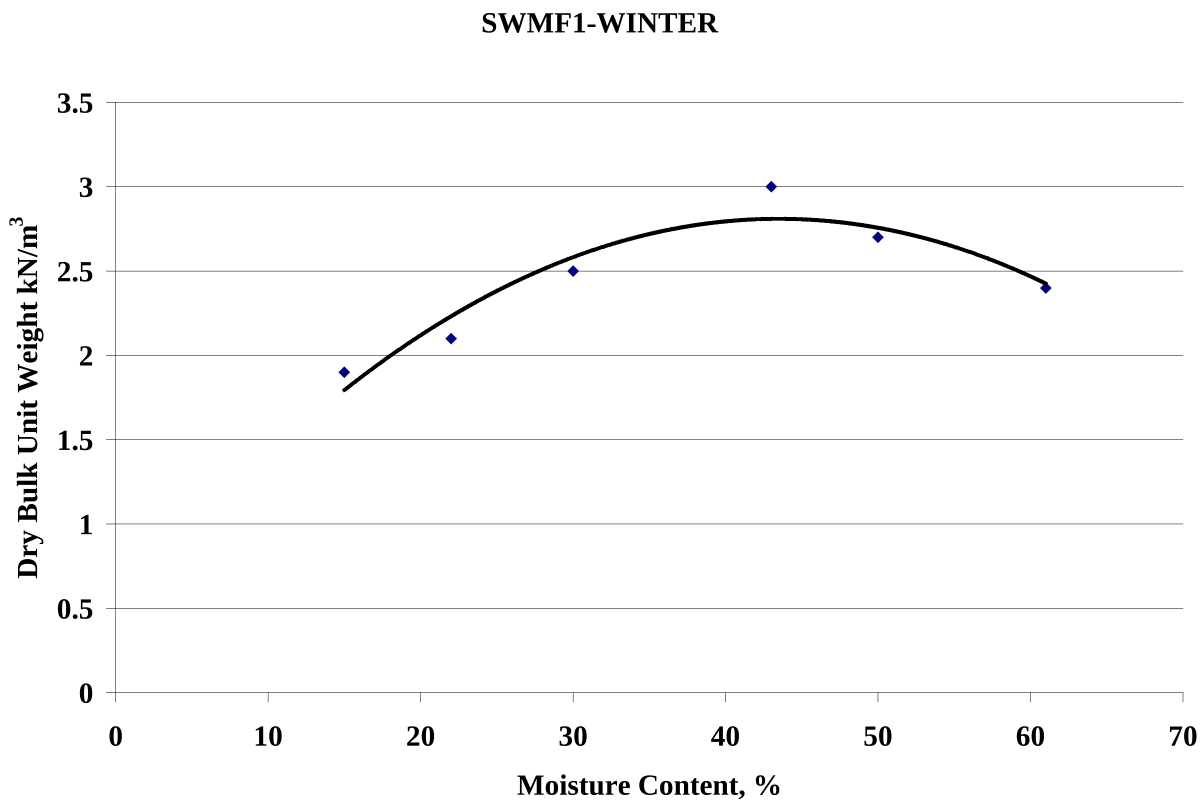
SWMF2b-FALL
Dry Bulk Unit Weight kN/m^3
3.5
3
2.5
2
1.5
1
0.5
0
0
10
20
30
40
50
60
70
Moisture Content, %

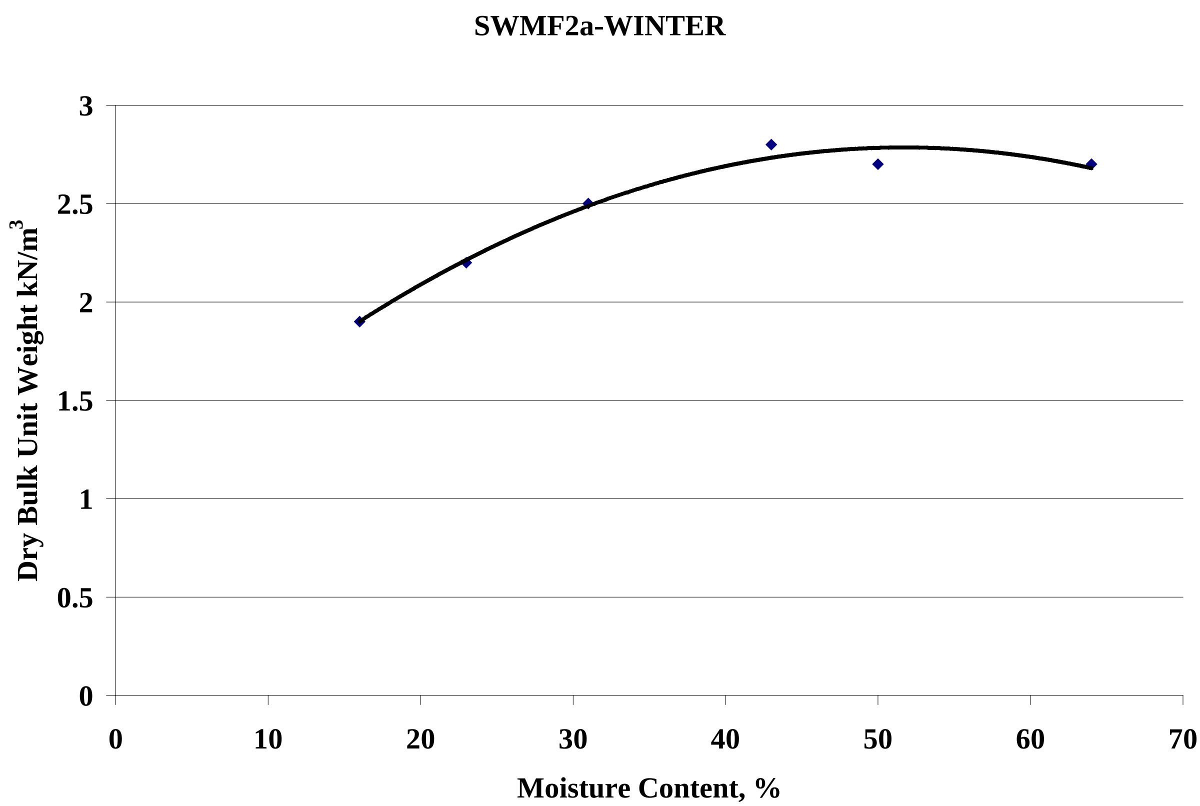

SWMF3-FALL
3.5
3
2.5
2
1.5
1
0.5
0
Dry Bulk Unit Weight kN/m3
0
10
20
30
40
50
60
70
Moisture Content, %

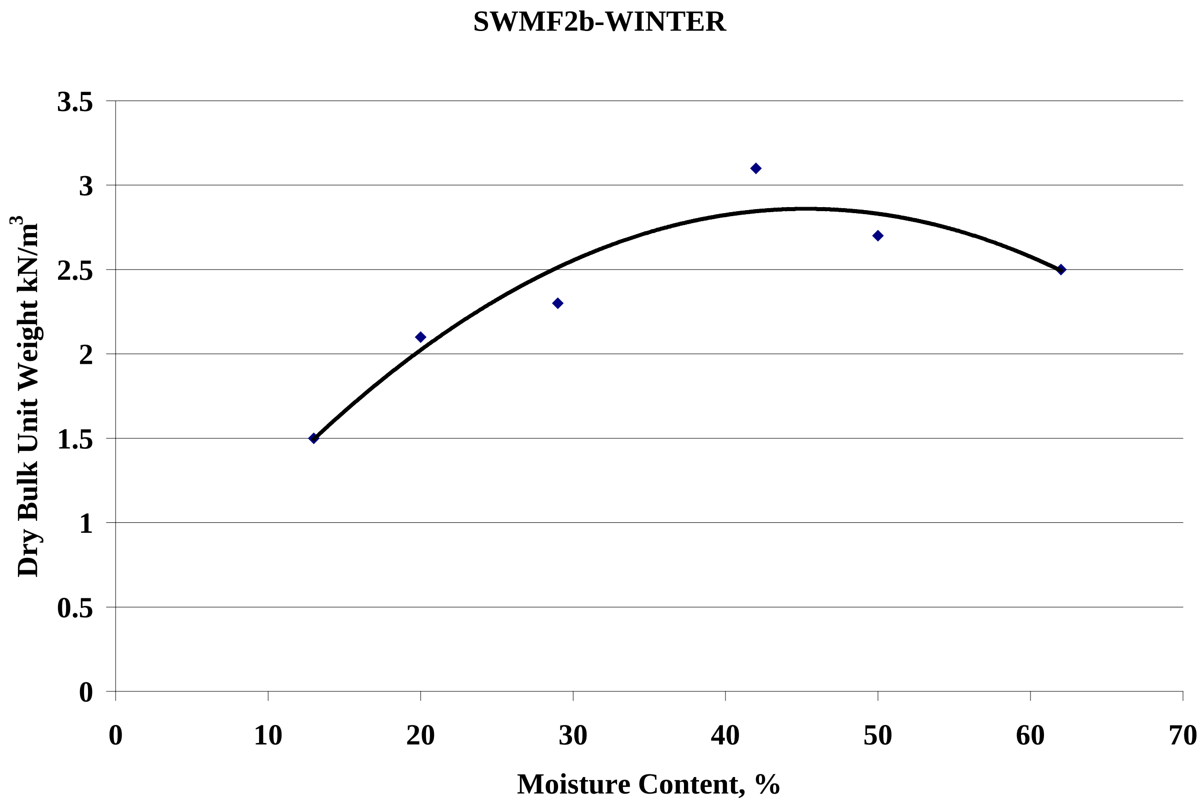

SWMF4-FALL
Dry Bulk Unit Weight kN/m3
Moisture Content, %
0
0.5
1
1.5
2
2.5
3
3.5
0
10
20
30
40
50
60
70

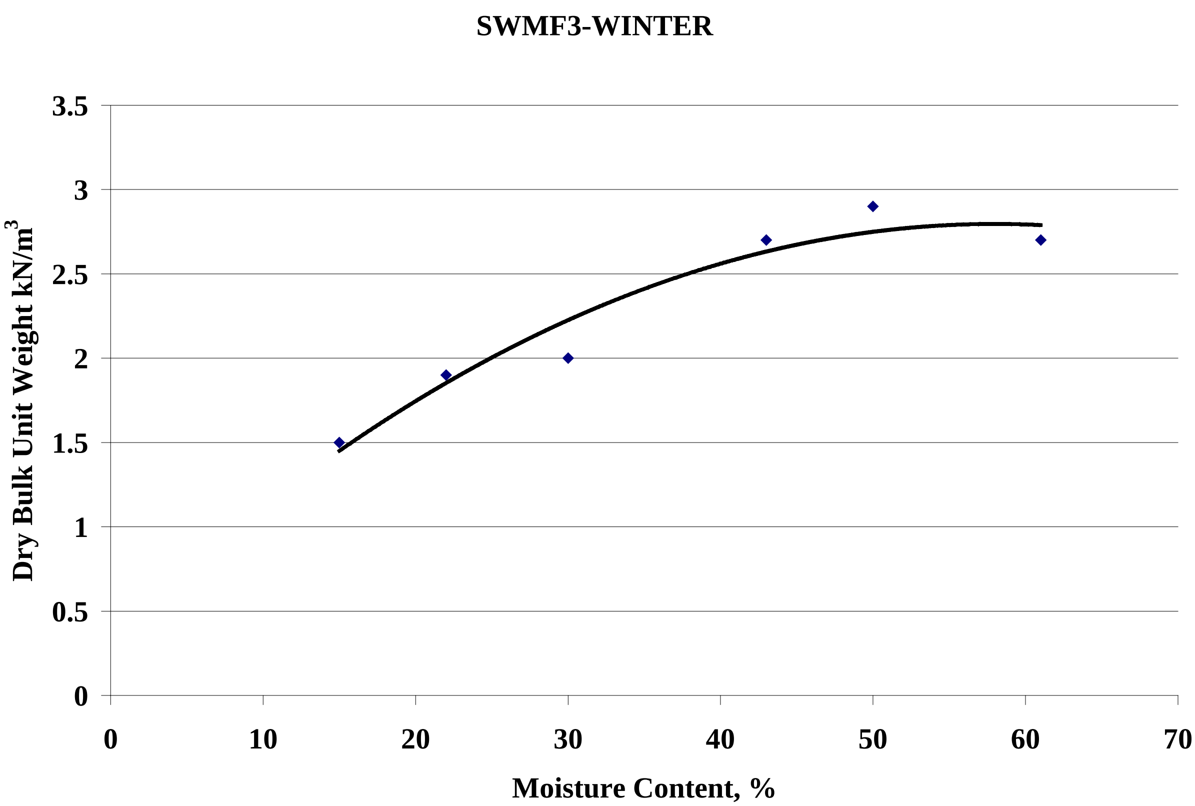

SWMF5-FALL
Dry Bulk Unit Weight kN/m3
3.5
3
2.5
2
1.5
1
0.5
0
0
10
20
30
40
50
60
70
Moisture Content, %

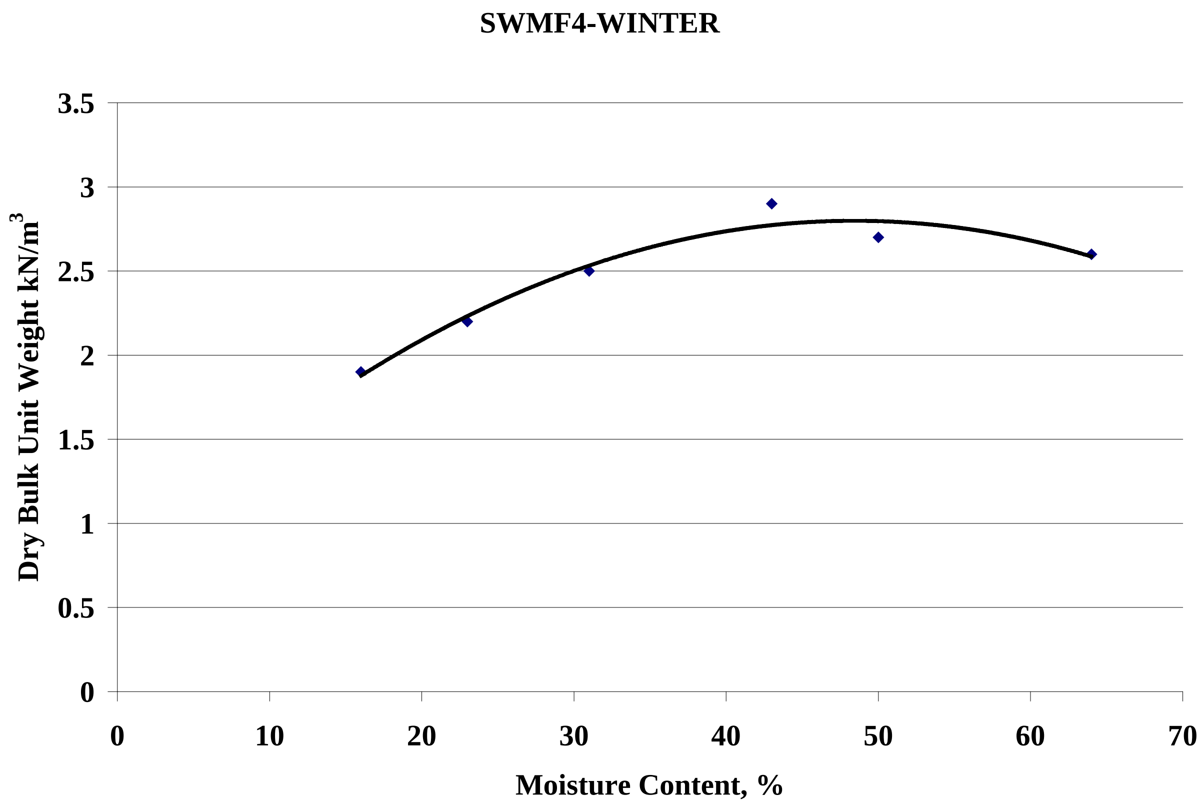
Fresh Mulch (Winter)



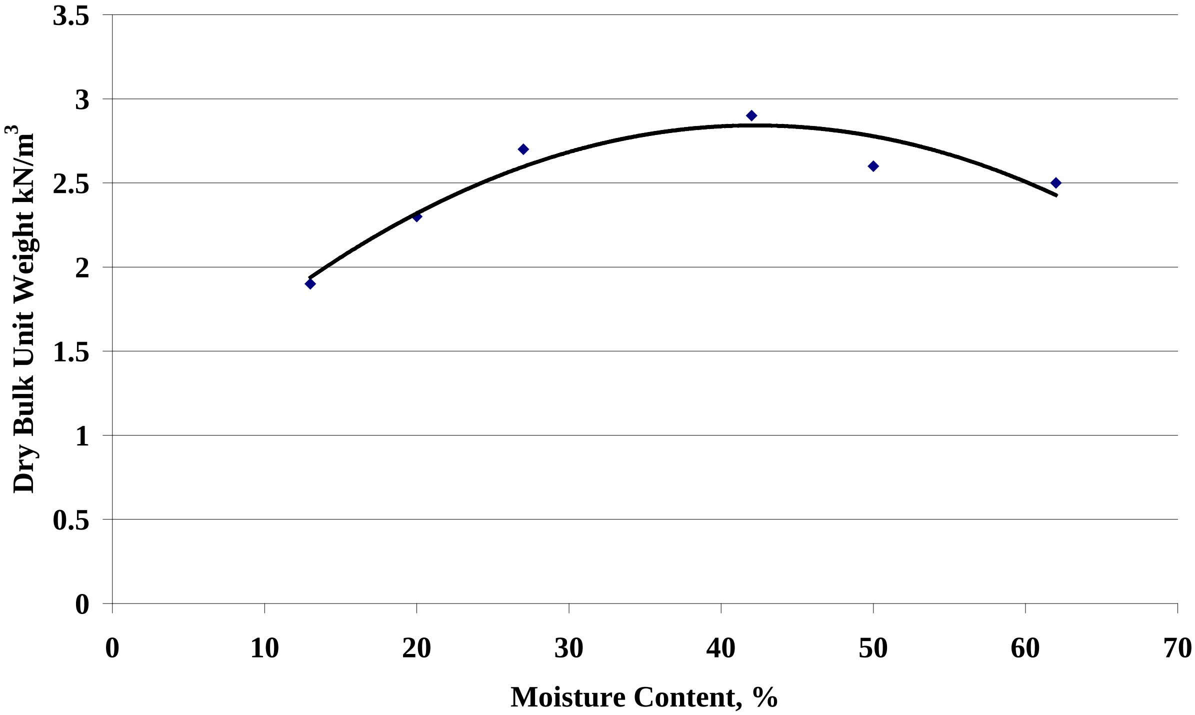

SWMF2a-WINTER
Dry Bulk Unit Weight kN/m3
Moisture Content, %
0
0.5
1
1.5
2
2.5
3
0
10
20
30
40
50
60
70


SWMF2b-WINTER
Dry Bulk Unit Weight kN/m3
3.5
3
2.5
2
1.5
1
0.5
0
0
10
20
30
40
50
60
70
Moisture Content, %

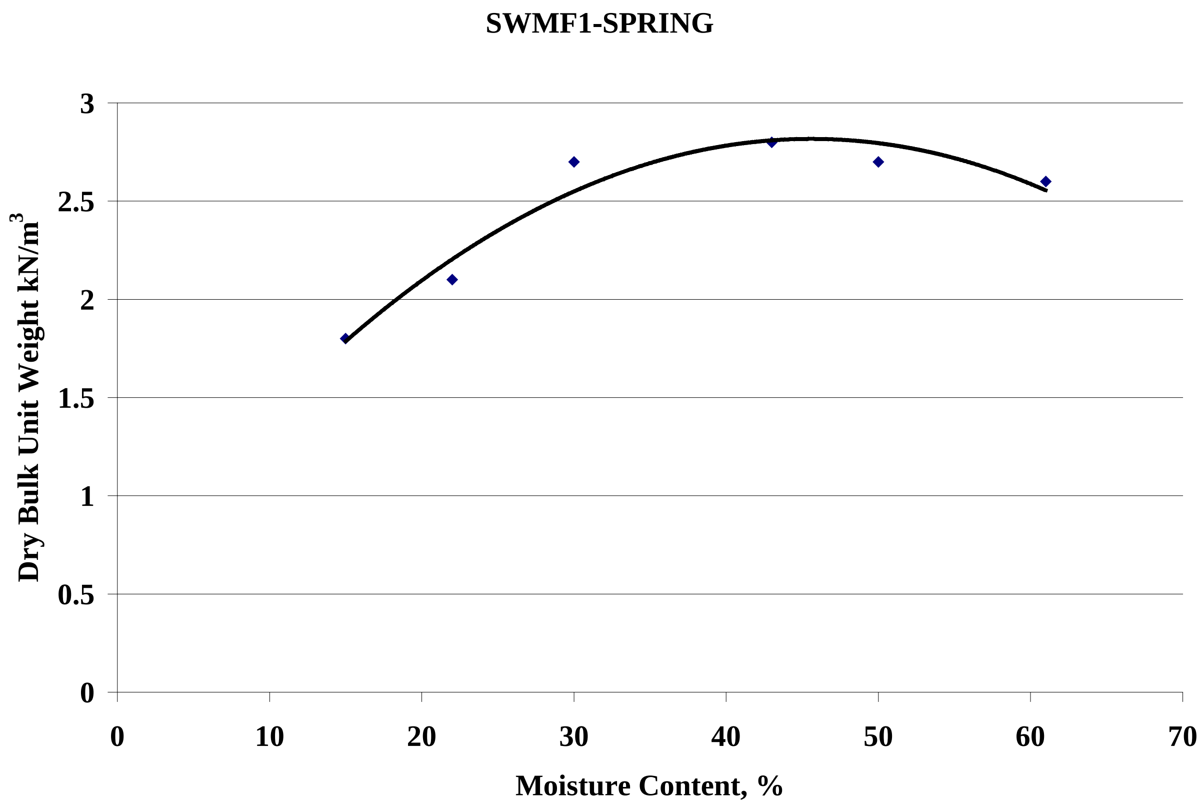

SWMF3-WINTER
Dry Bulk Unit Weight kN/m3
3.5
3
2.5
2
1.5
1
0.5
0
0
10
20
30
40
50
60
70
Moisture Content, %

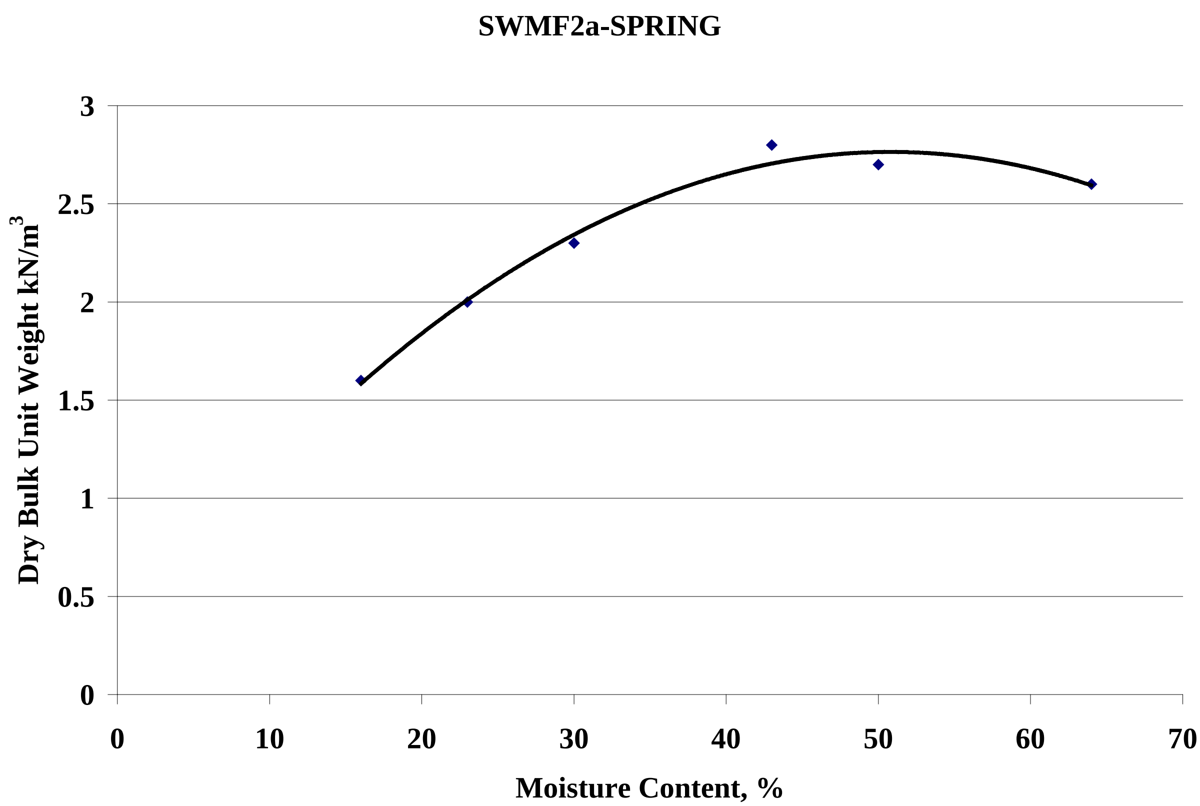

SWMF4-WINTER
Dry Bulk Unit Weight kN/m3
3.5
3
2.5
2
1.5
1
0.5
0
0
10
20
30
40
50
60
70
Moisture Content, %

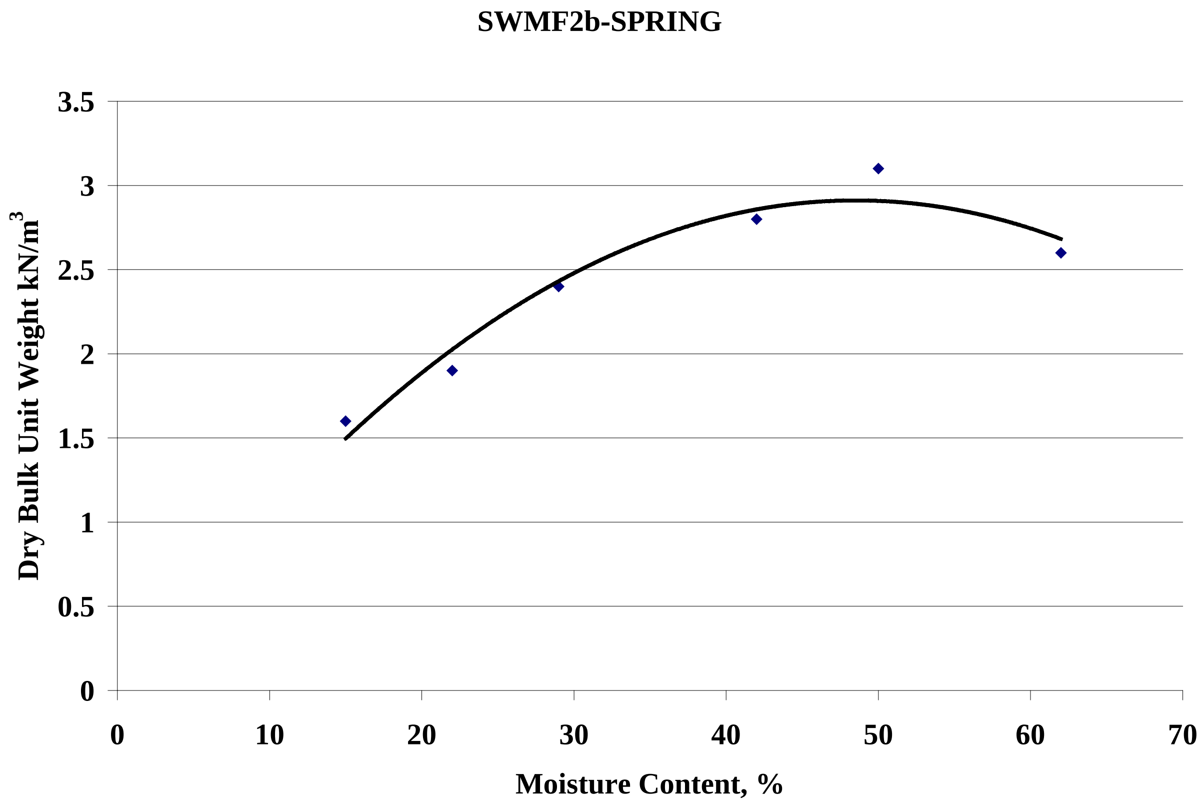
SWMF5-WINTER



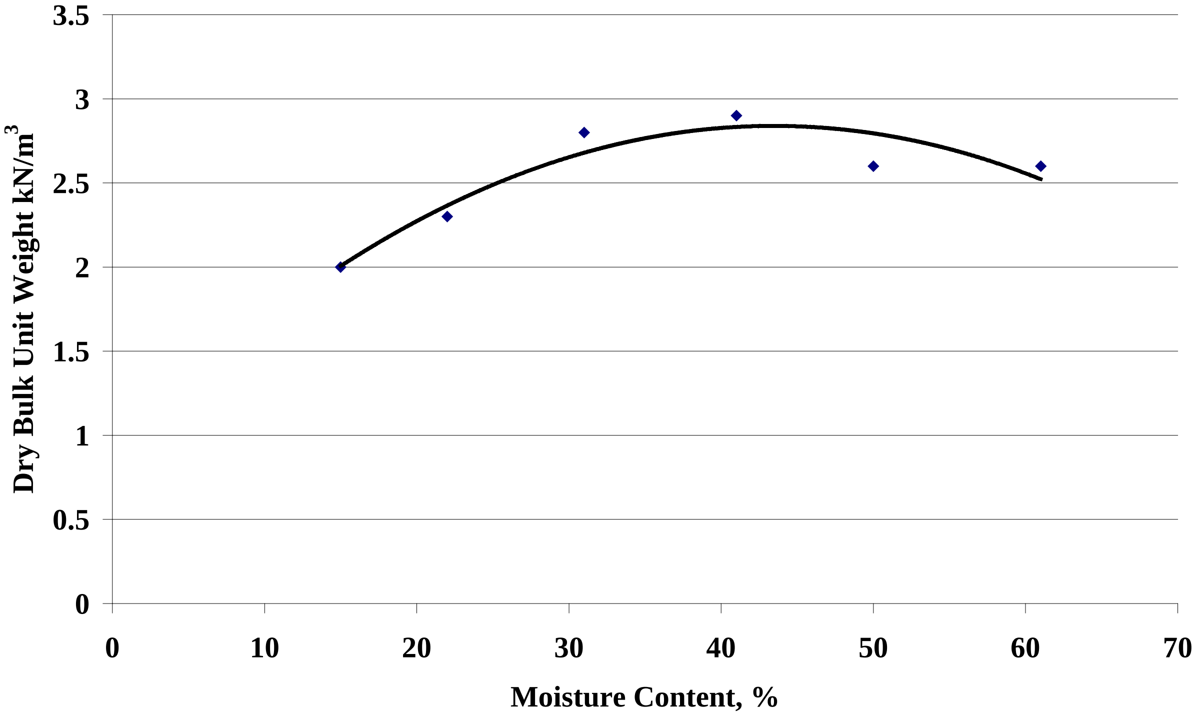
Fresh Mulch (Spring)

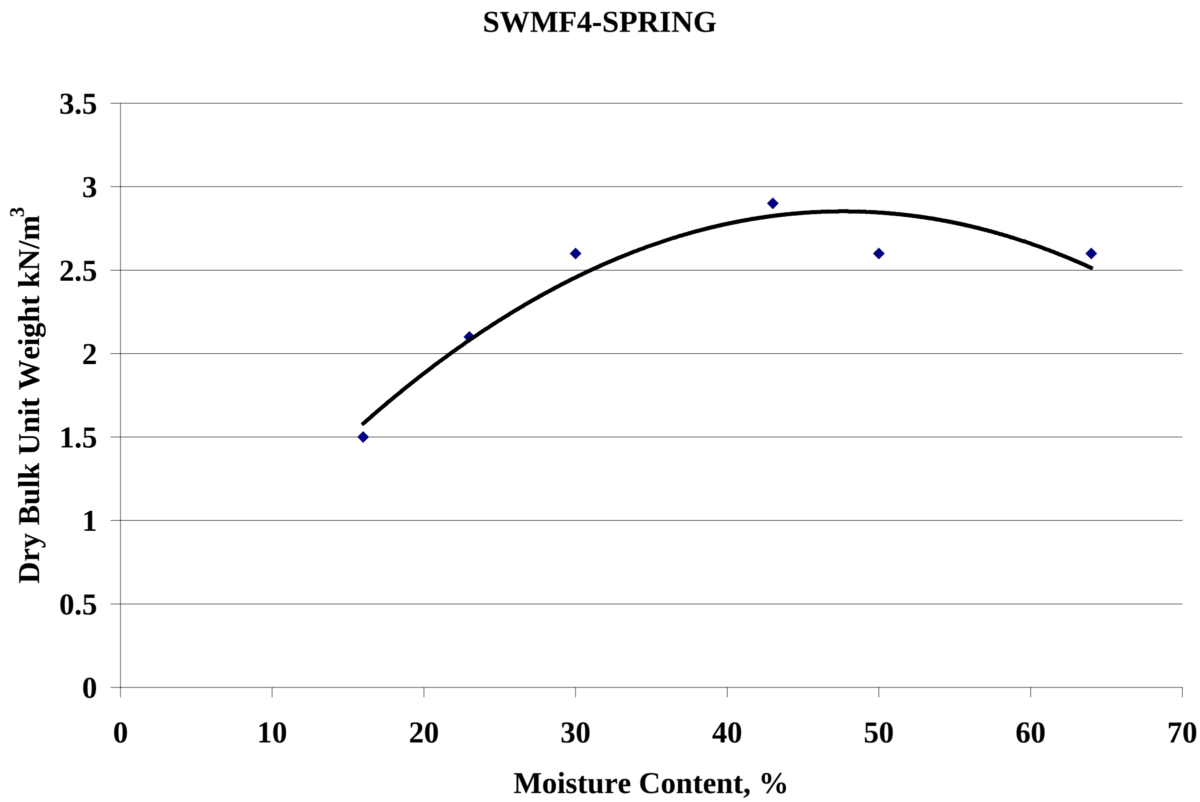


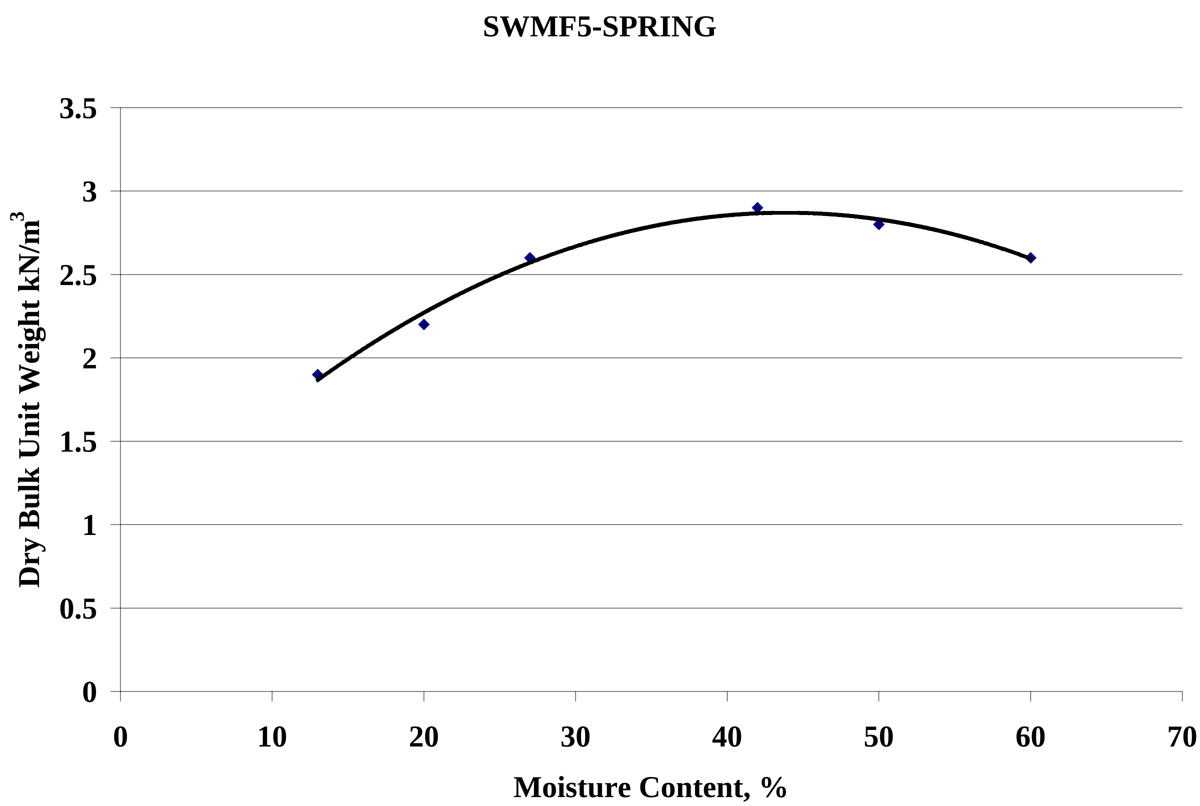

SWMF2a-SPRING
Dry Bulk Unit Weight kN/m3
3
2.5
2
1.5
1
0.5
0
0
10
20
30
40
50
60
70
Moisture Content, %


SWMF2b-SPRING
3.5
3
2.5
2
1.5
1
0.5
0
0
10
20
30
40
50
60
70
Dry Bulk Unit Weight kN/m3
Moisture Content, %

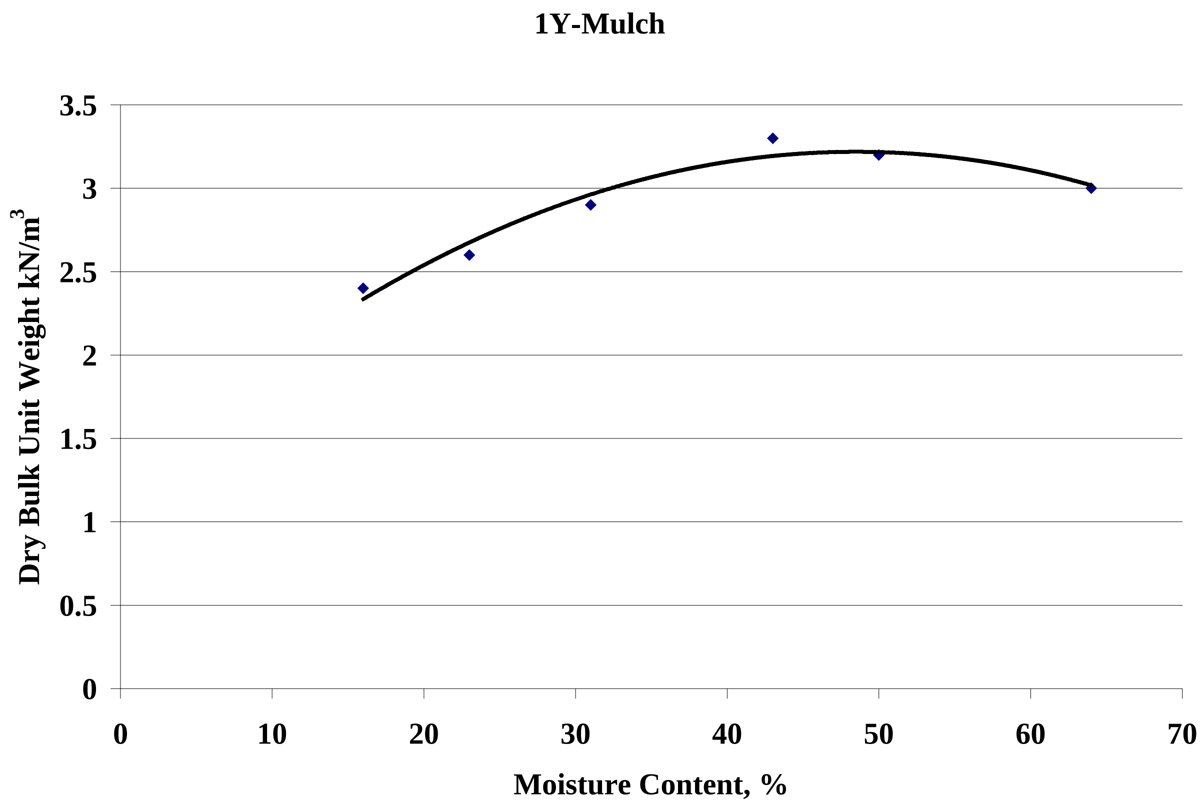
SWMF3-SPRING




SWMF4-SPRING
Dry Bulk Unit Weight kN/m3
3.5
3
2.5
2
1.5
1
0.5
0
0
10
20
30
40
50
60
70
Moisture Content, %

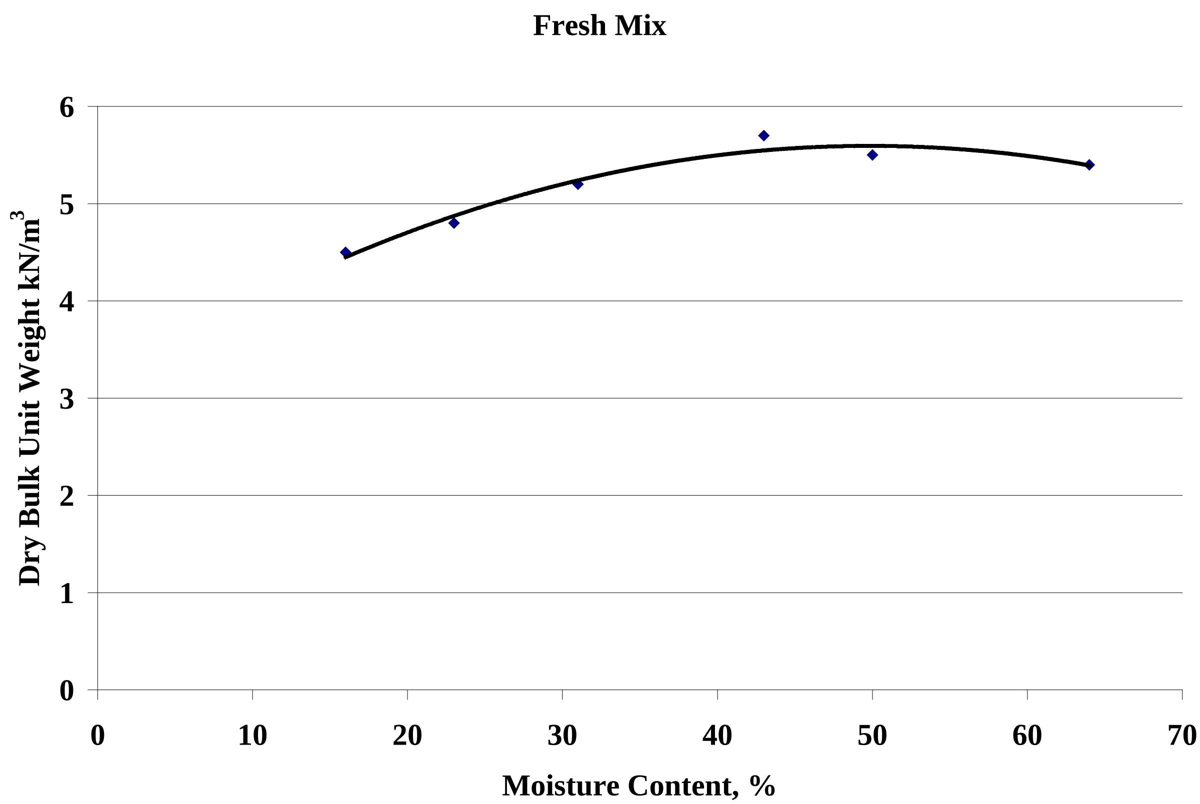

SWMF5-SPRING
Dry Bulk Unit Weight kN/m3
Moisture Content, %
0
0.5
1
1.5
2
2.5
3
3.5
0
10
20
30
40
50
60
70

1Y-Mulch



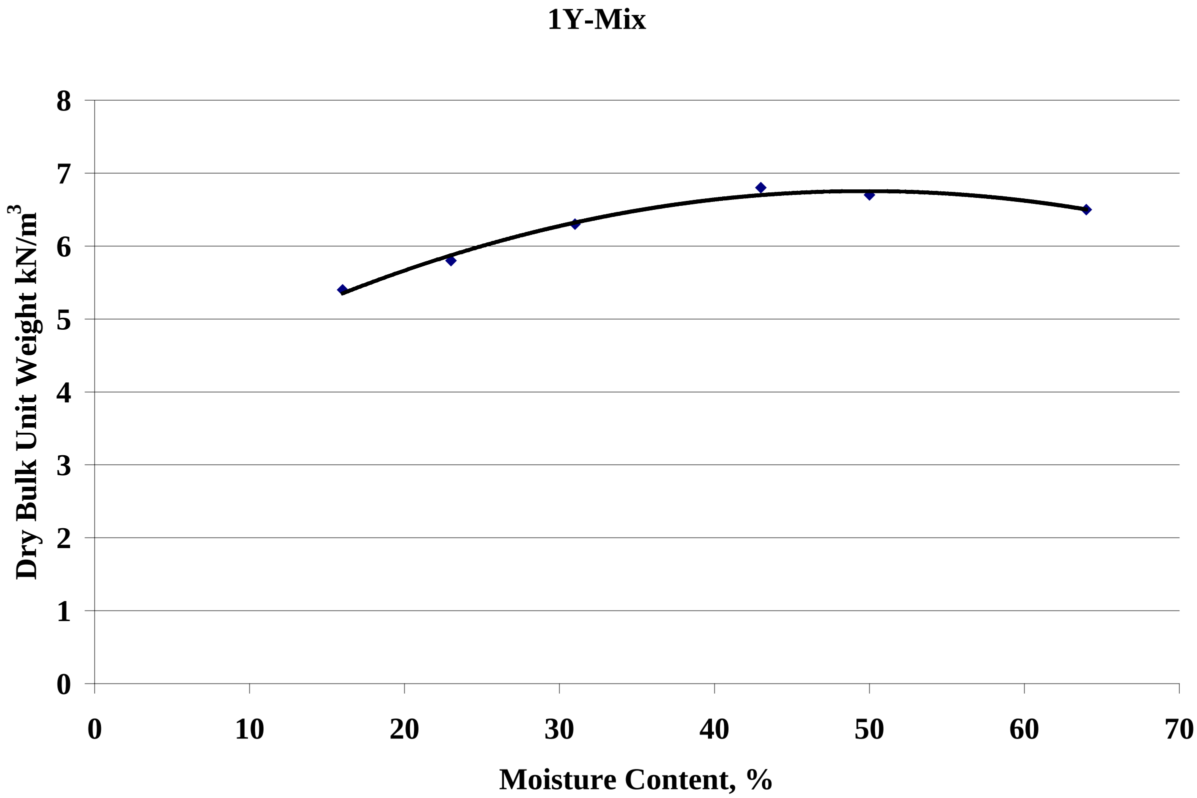
1Y-Mulch
Dry Bulk Unit Weight kN/m3
3.5
3
2.5
2
1.5
1
0.5
0
0
10
20
30
40
50
60
70
Moisture Content, %

Fresh Mix

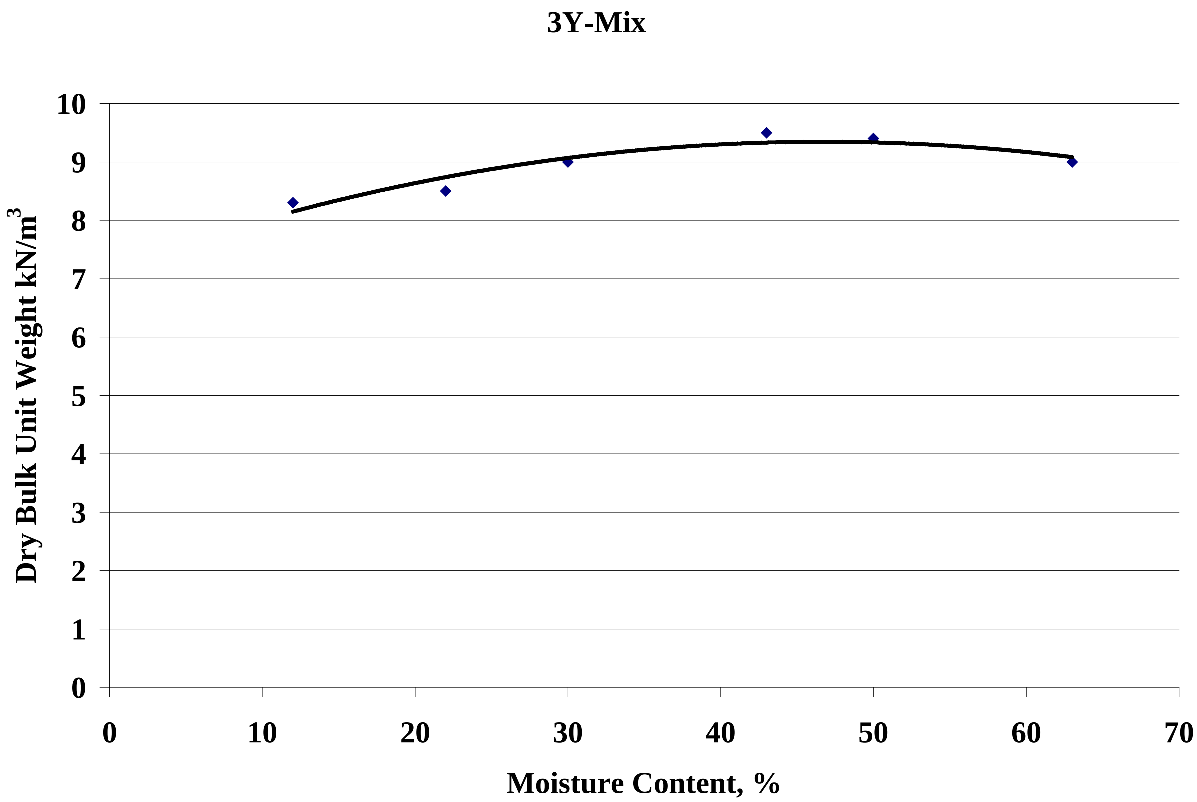


Fresh Mix
Dry Bulk Unit Weight kN/m3
6
5
4
3
2
1
0
0
10
20
30
40
50
60
70
Moisture Content, %

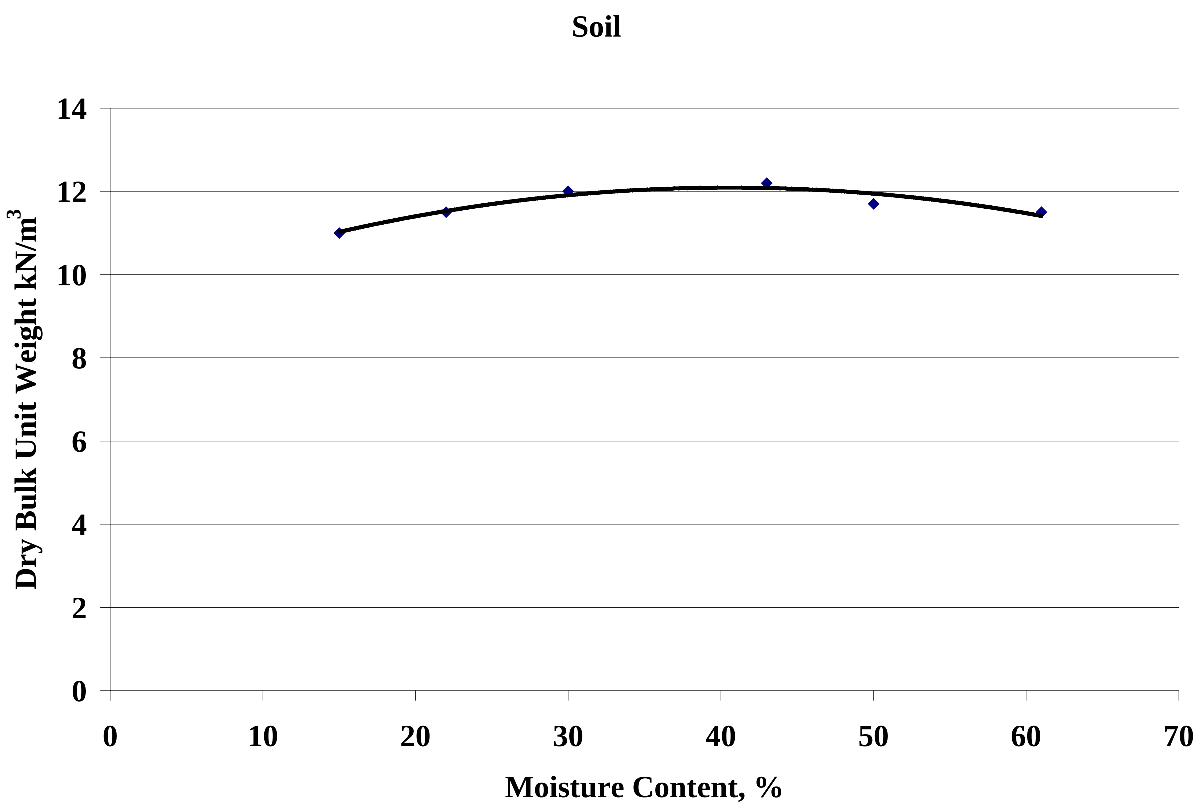
<u>1Y-Mix</u>


1Y-Mix
Dry Bulk Unit Weight kN/m3
8
7
6
5
4
3
2
1
0
0
10
20
30
40
50
60
70
Moisture Content, %

3Y-Mix


3Y-Mix
Dry Bulk Unit Weight kN/m3
Moisture Content, %
0
1
2
3
4
5
6
7
8
9
10
0
10
20
30
40
50
60
70

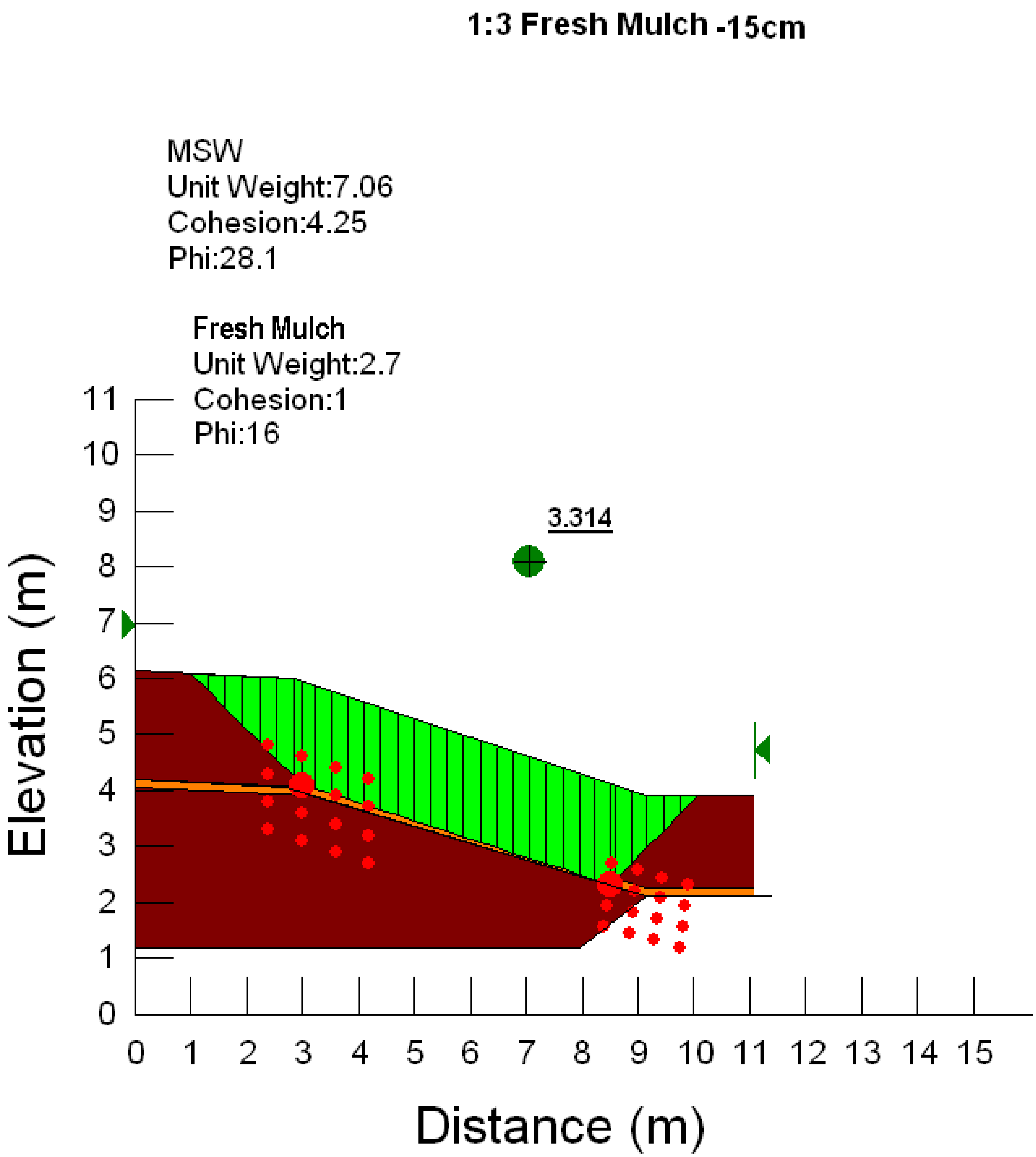
<u>Soil</u>

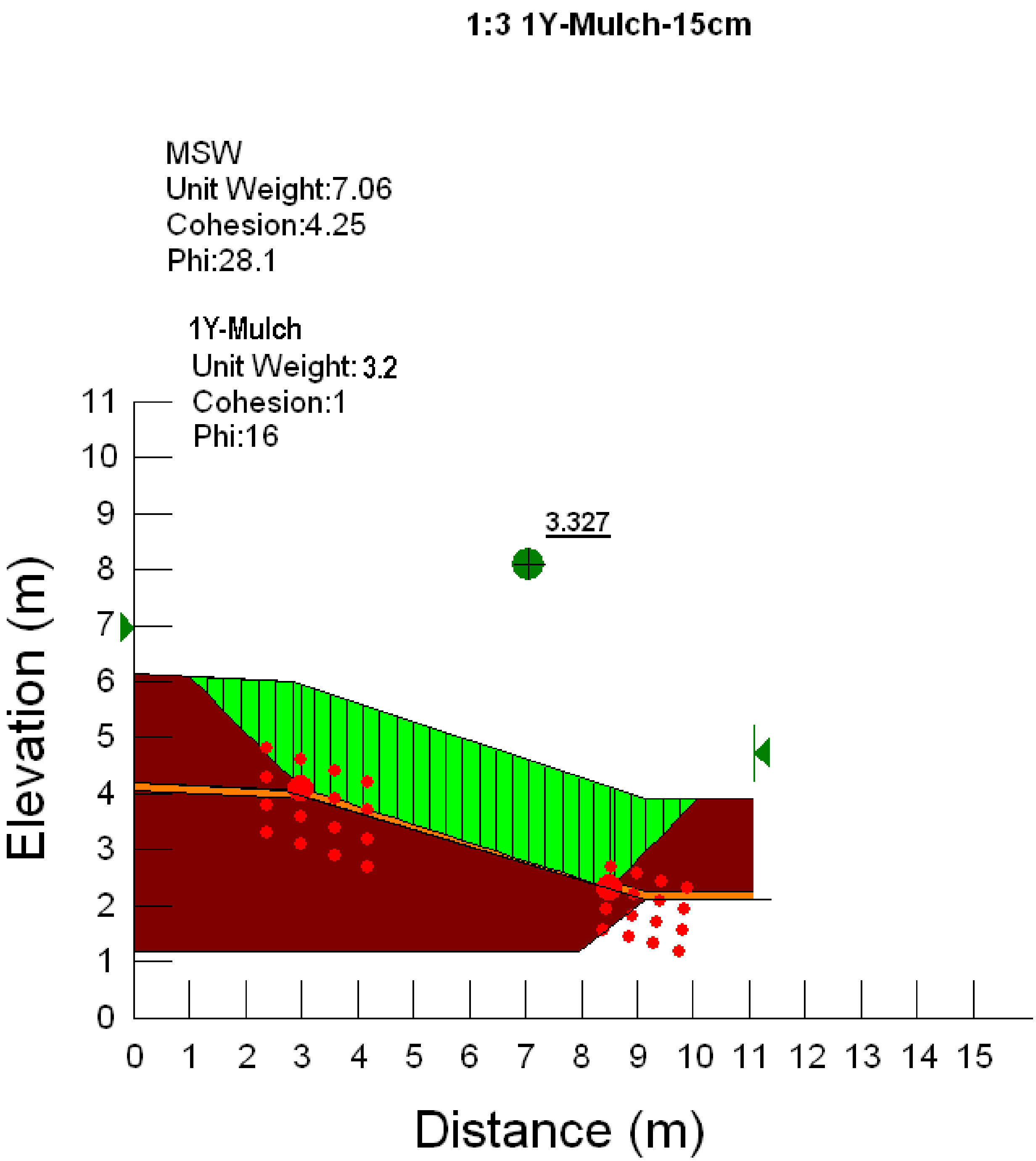


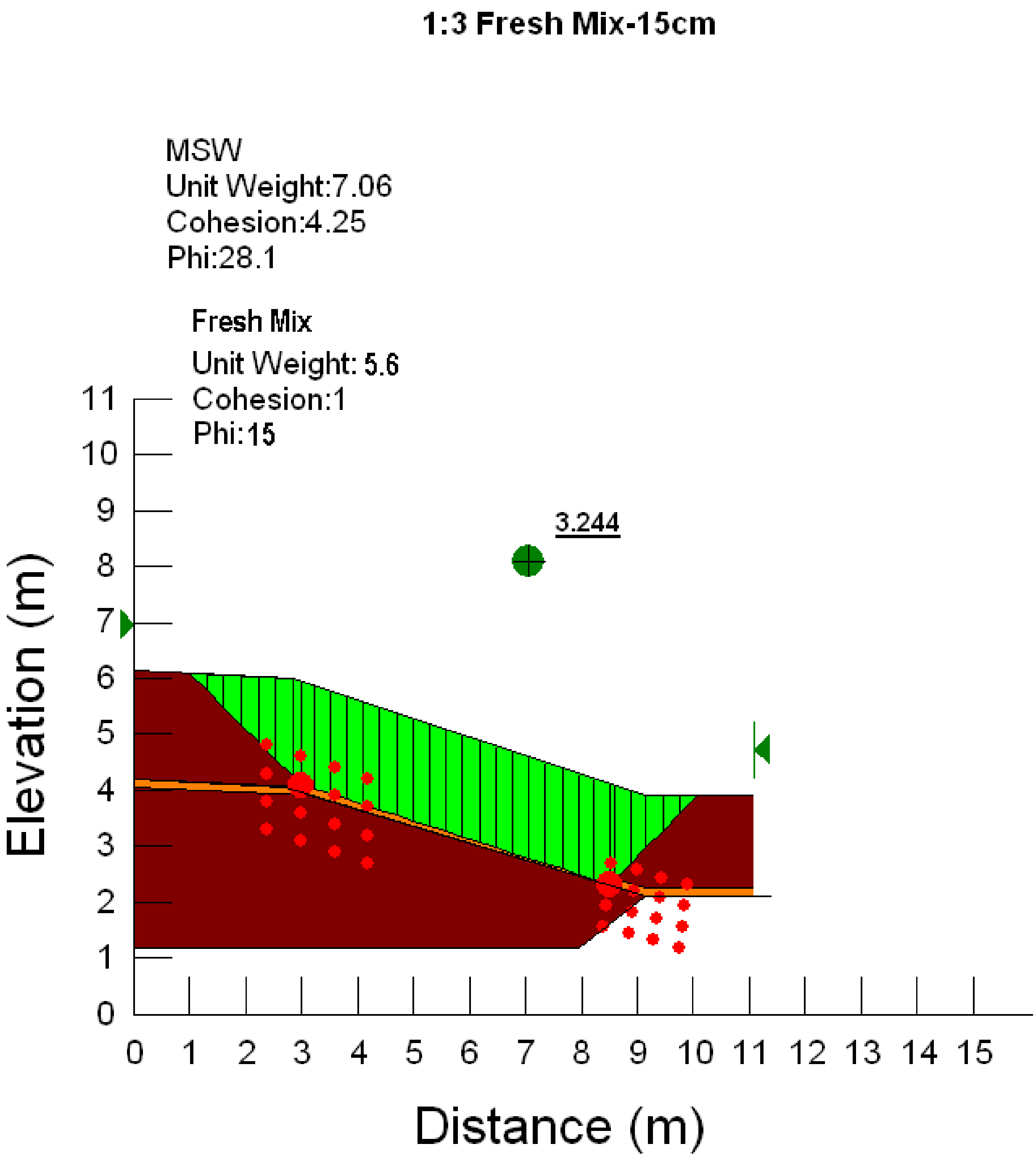
Soil
14
12
10
8
6
4
2
0
0
10
20
30
40
50
60
70
Dry Bulk Unit Weight kN/m3
Moisture Content, %

APPENDIX C: SLOPE /W MODELING

Block Failure (Slope 1:3 / Cover Depth = 15cm)

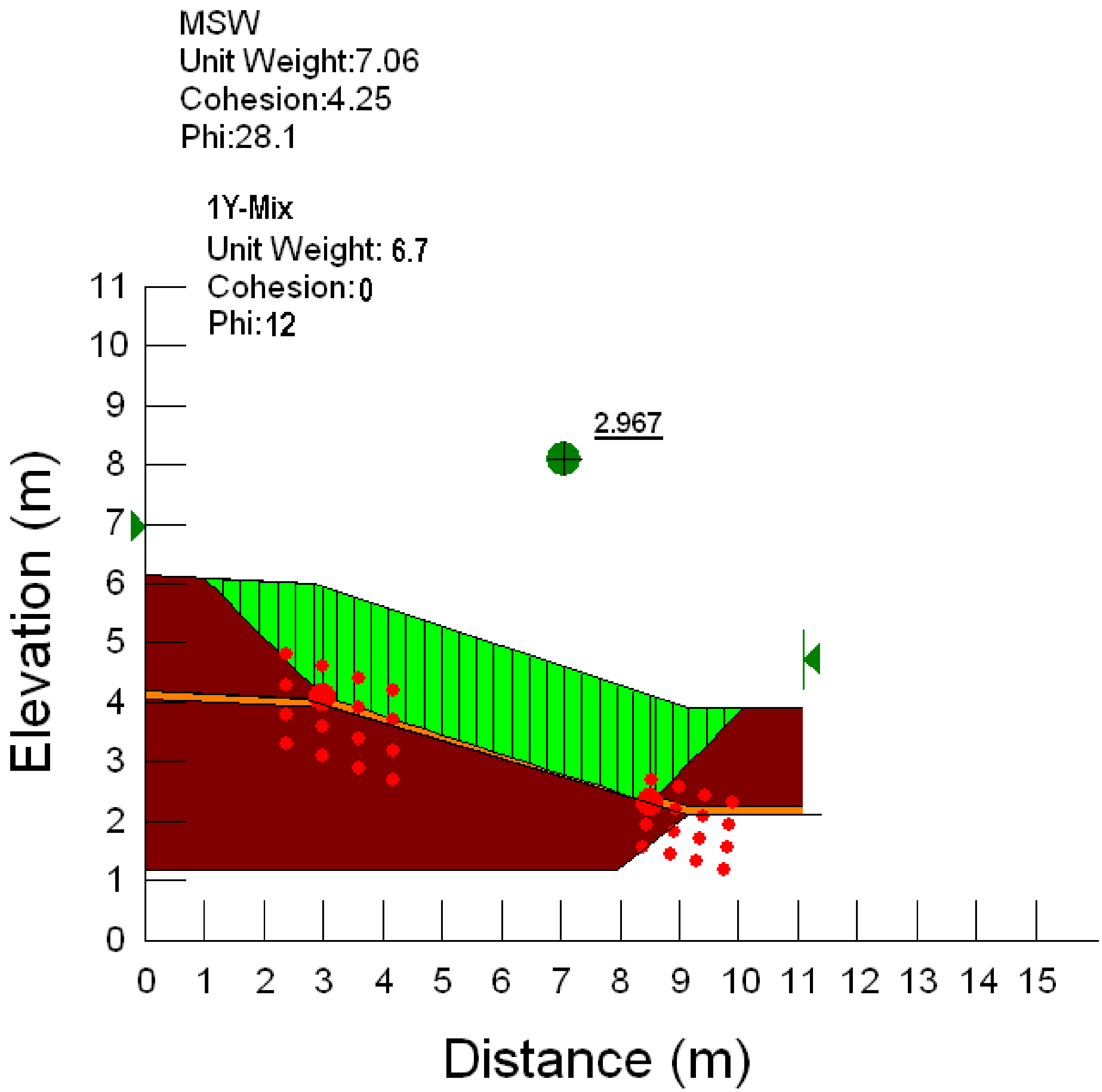



1:3 1Y-Mulch-15cm
MSW
Unit Weight:7.06
Cohesion:4.25
Phi:28.1
1Y-Mulch
Unit Weight: 3.2
Cohesion:1
Phi:16
3.327
Elevation (m)
Distance (m)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

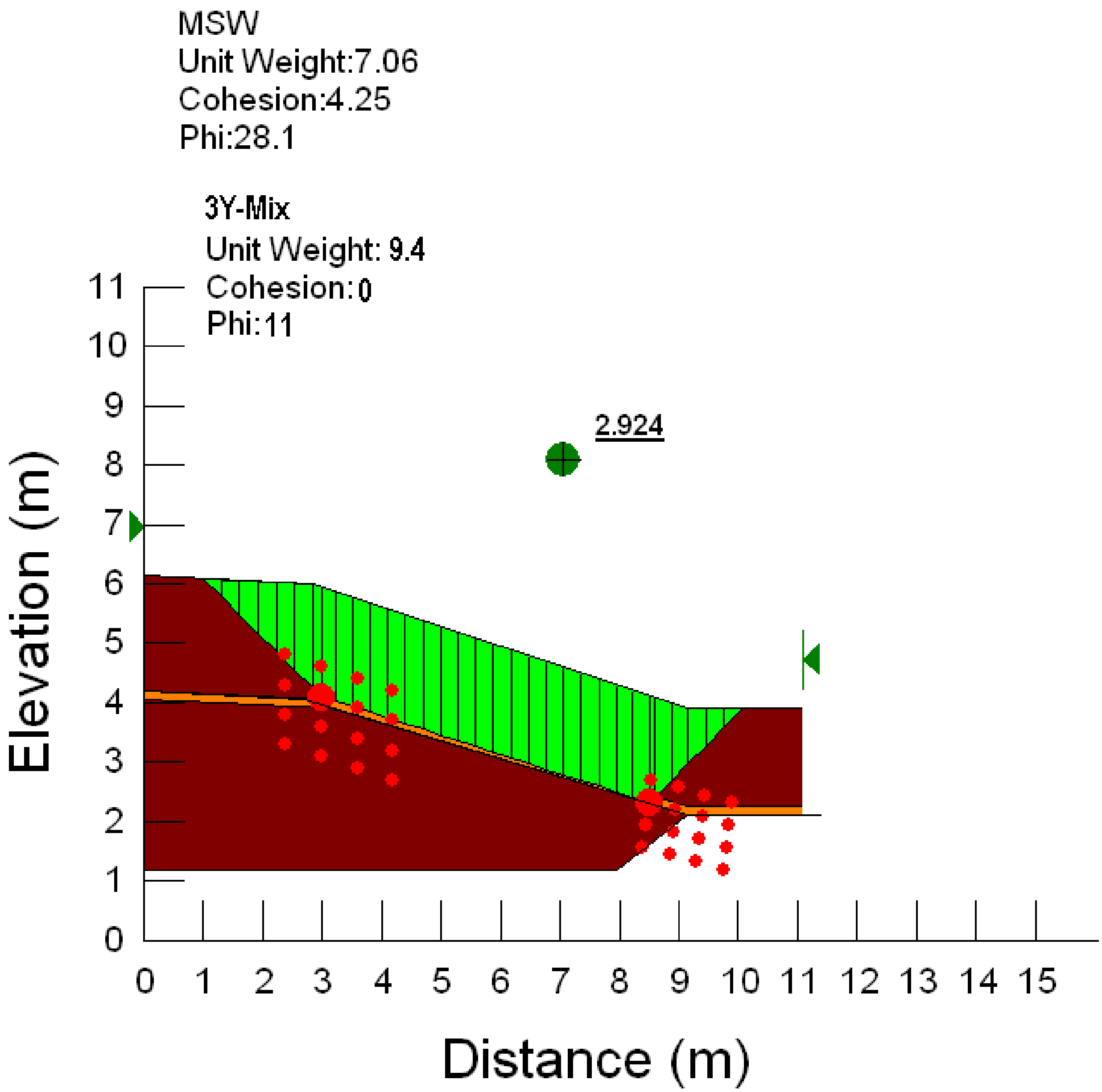


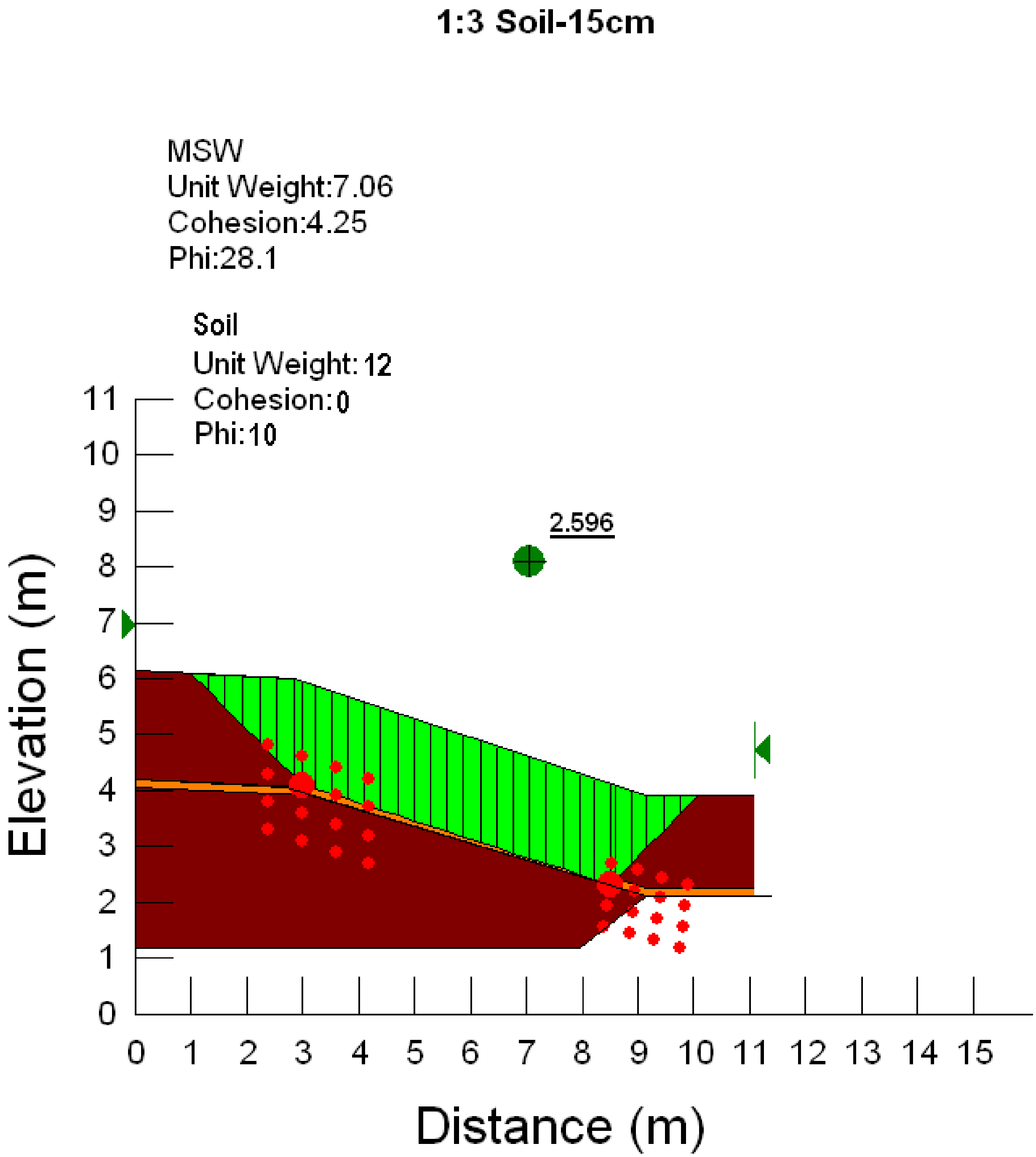
1:3 Fresh Mix-15cm
MSW
Unit Weight:7.06
Cohesion:4.25
Phi:28.1
Fresh Mix
Unit Weight: 5.6
Cohesion:1
Phi:15
3.244
Elevation (m)
Distance (m)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

1:3 1Y-Mix-15cm

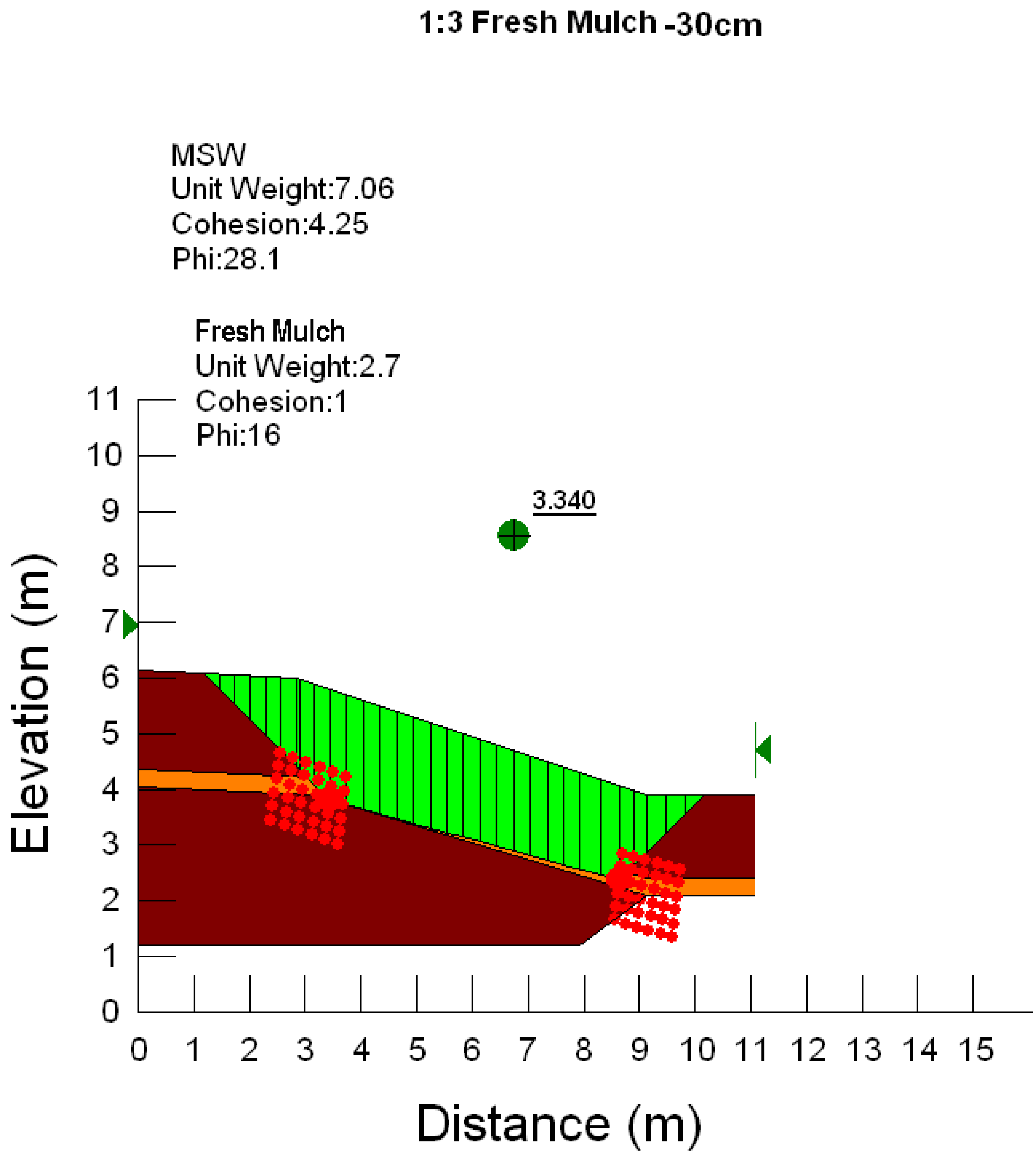


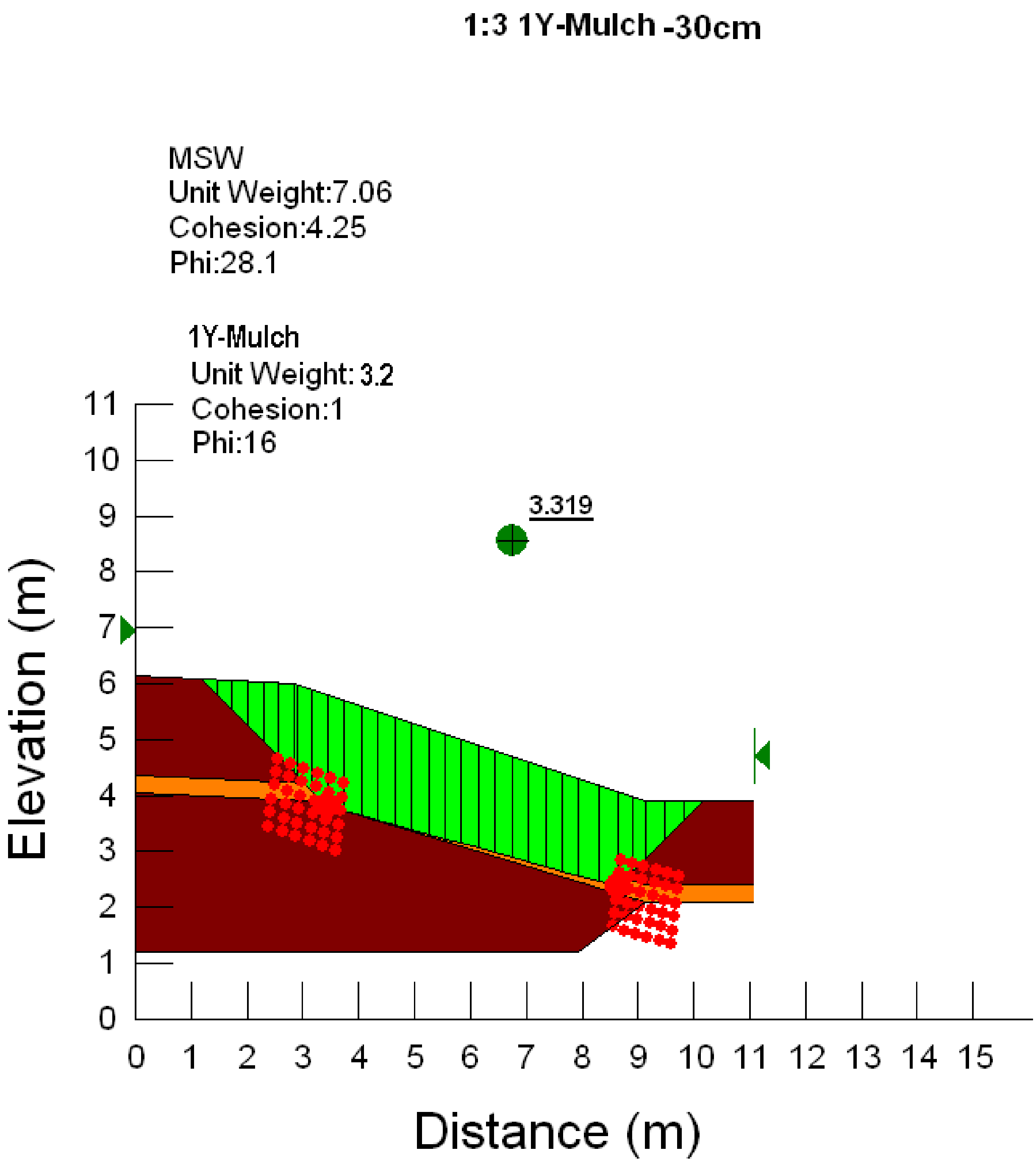
1:3 3Y-Mix-15cm



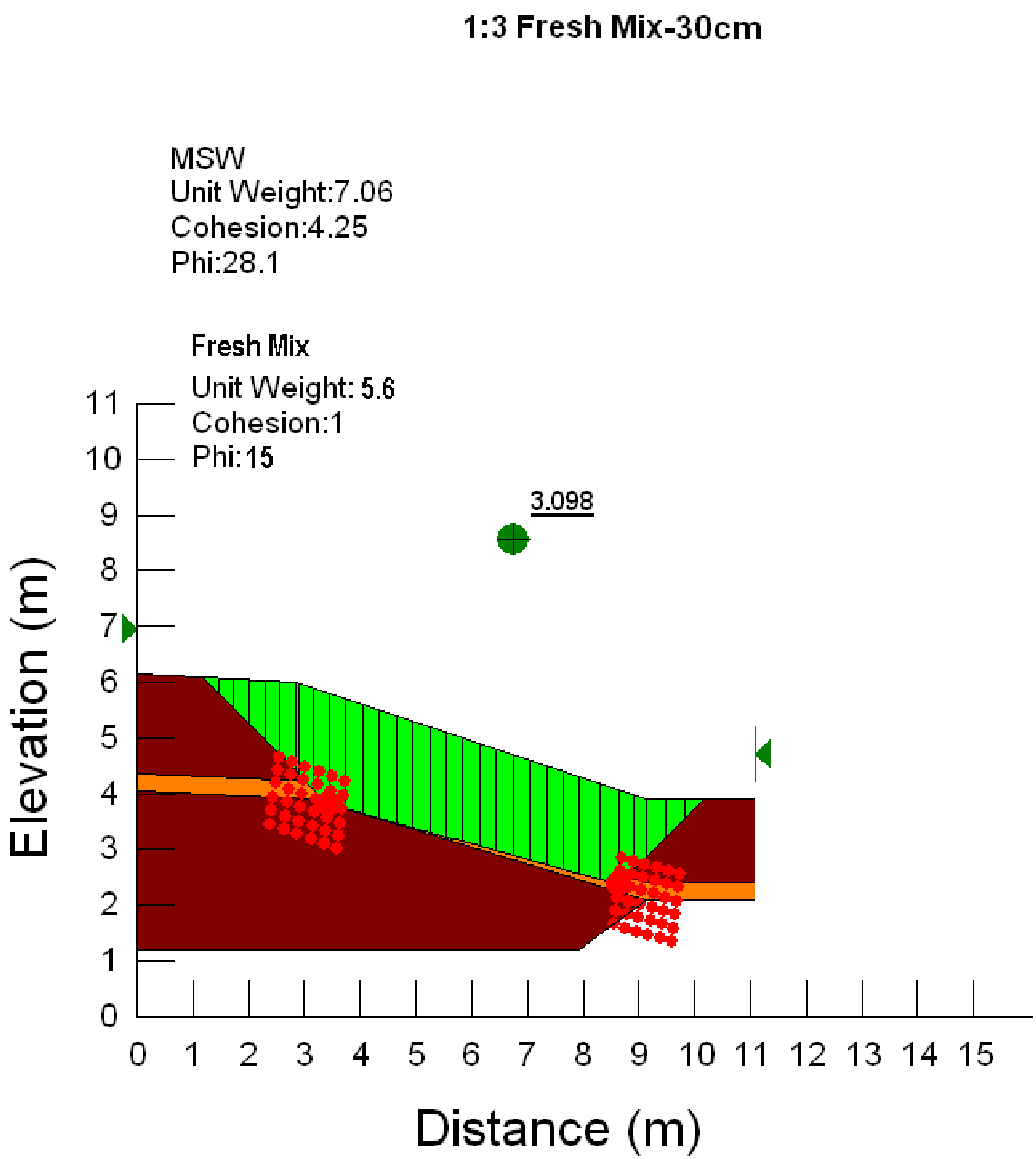

1:3 Soil-15cm
MSW
Unit Weight:7.06
Cohesion:4.25
Phi:28.1
Soil
Unit Weight: 12
Cohesion: 0
Phi: 10
2.596
Elevation (m)
Distance (m)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

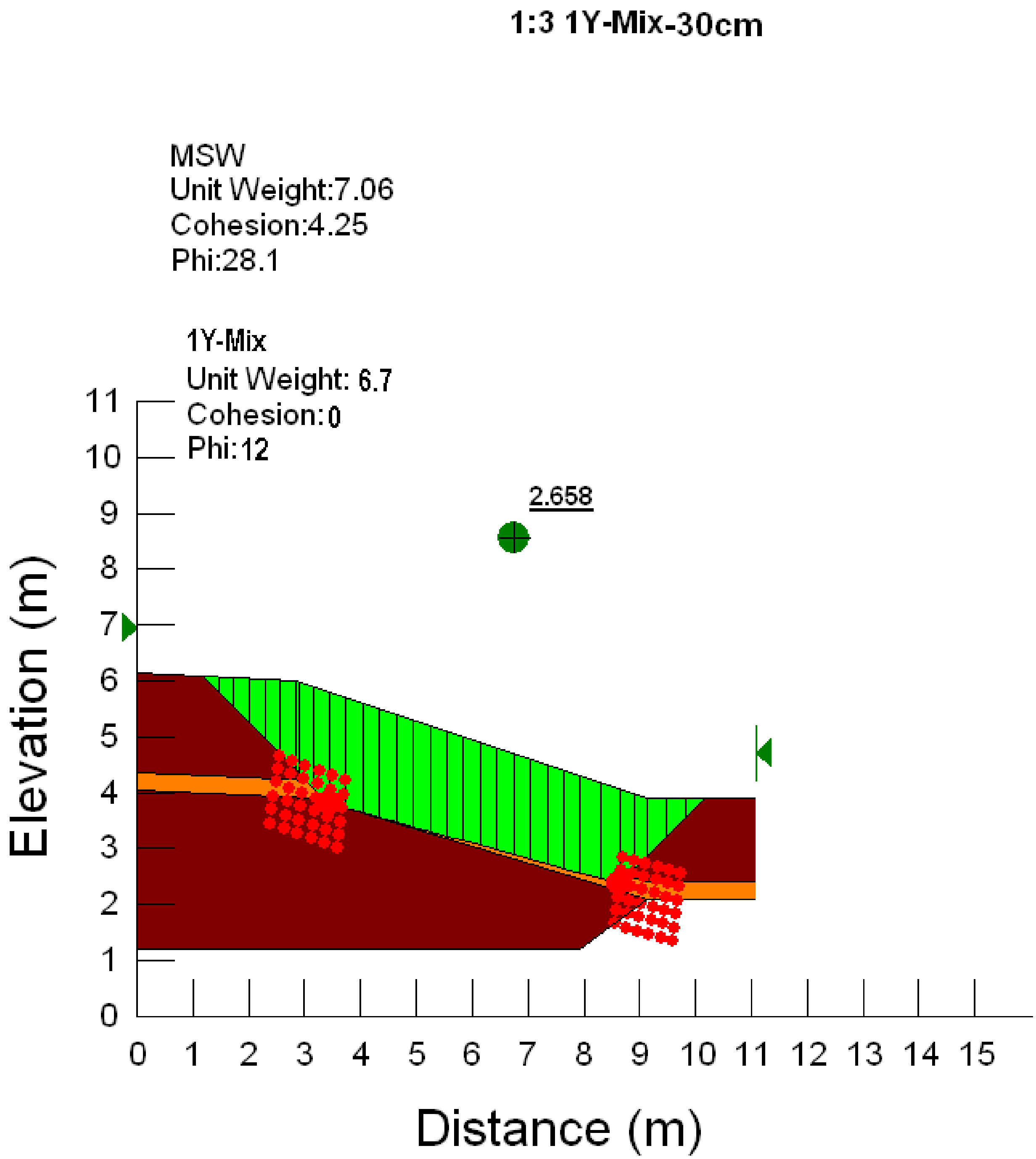
Block Failure (Slope 1:3 / Cover Depth = 30cm)

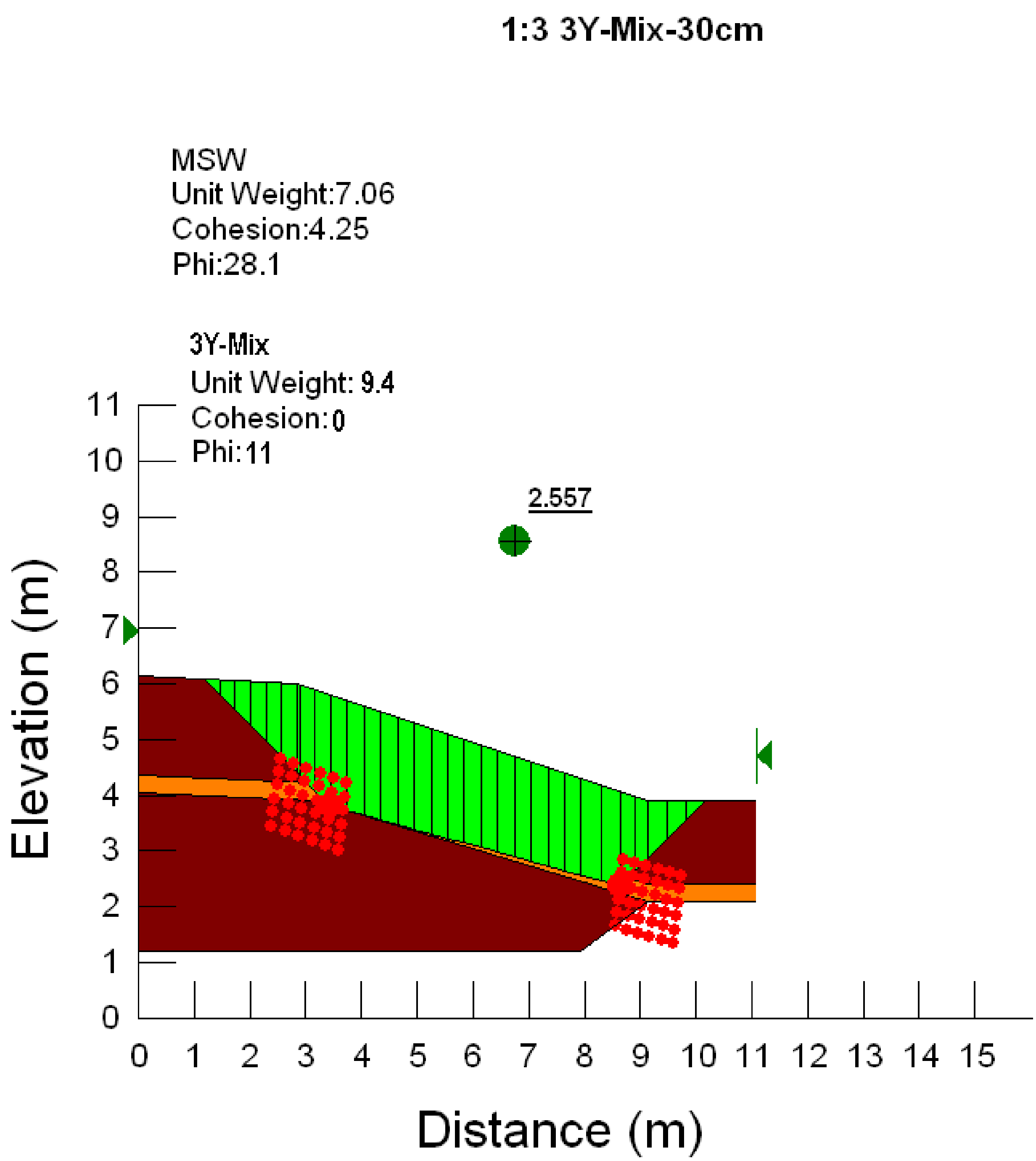


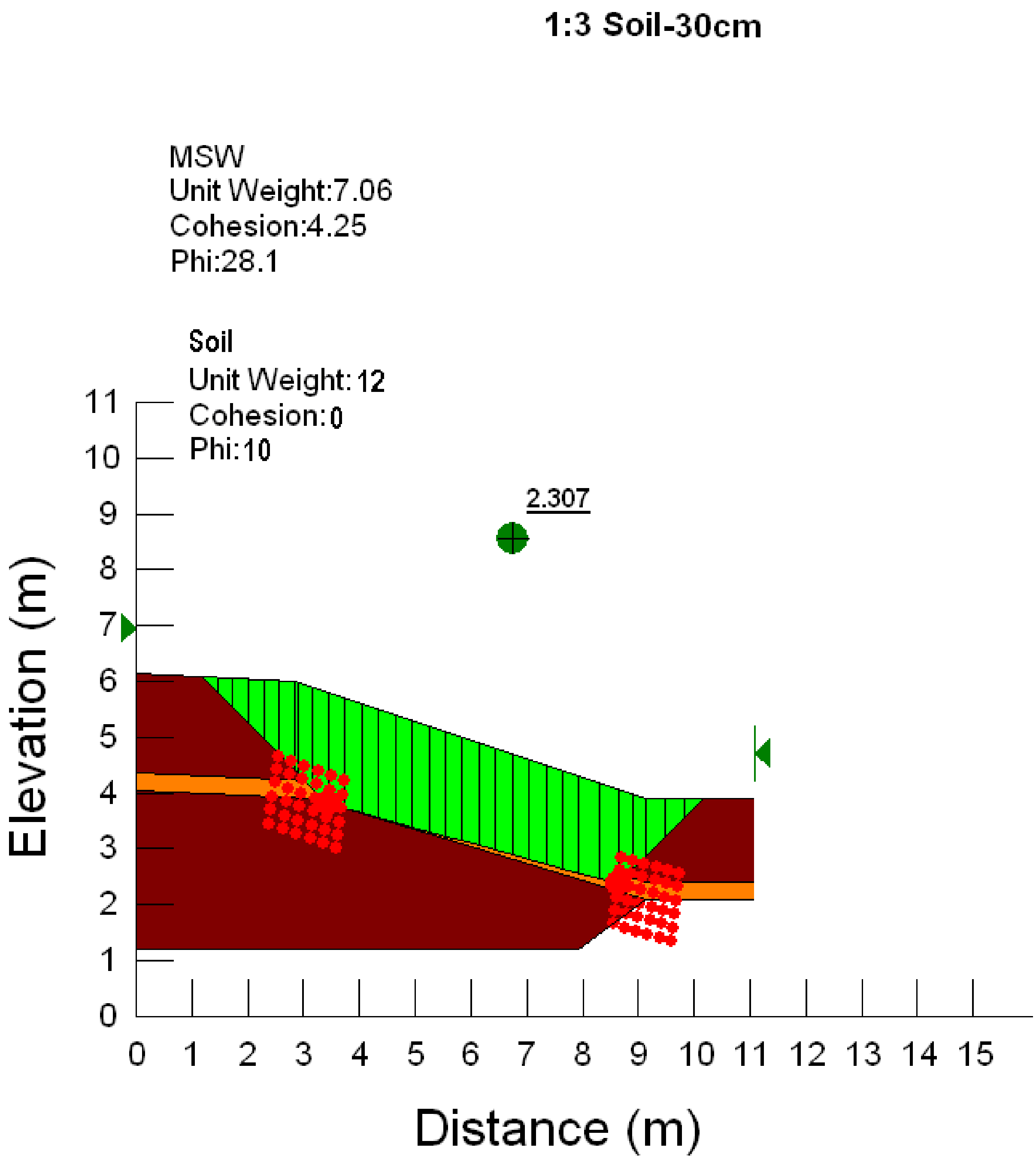


1:3 1Y-Mulch -30cm
MSW
Unit Weight:7.06
Cohesion:4.25
Phi:28.1
1Y-Mulch
Unit Weight: 3.2
Cohesion:1
Phi:16
3.319
Elevation (m)
Distance (m)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

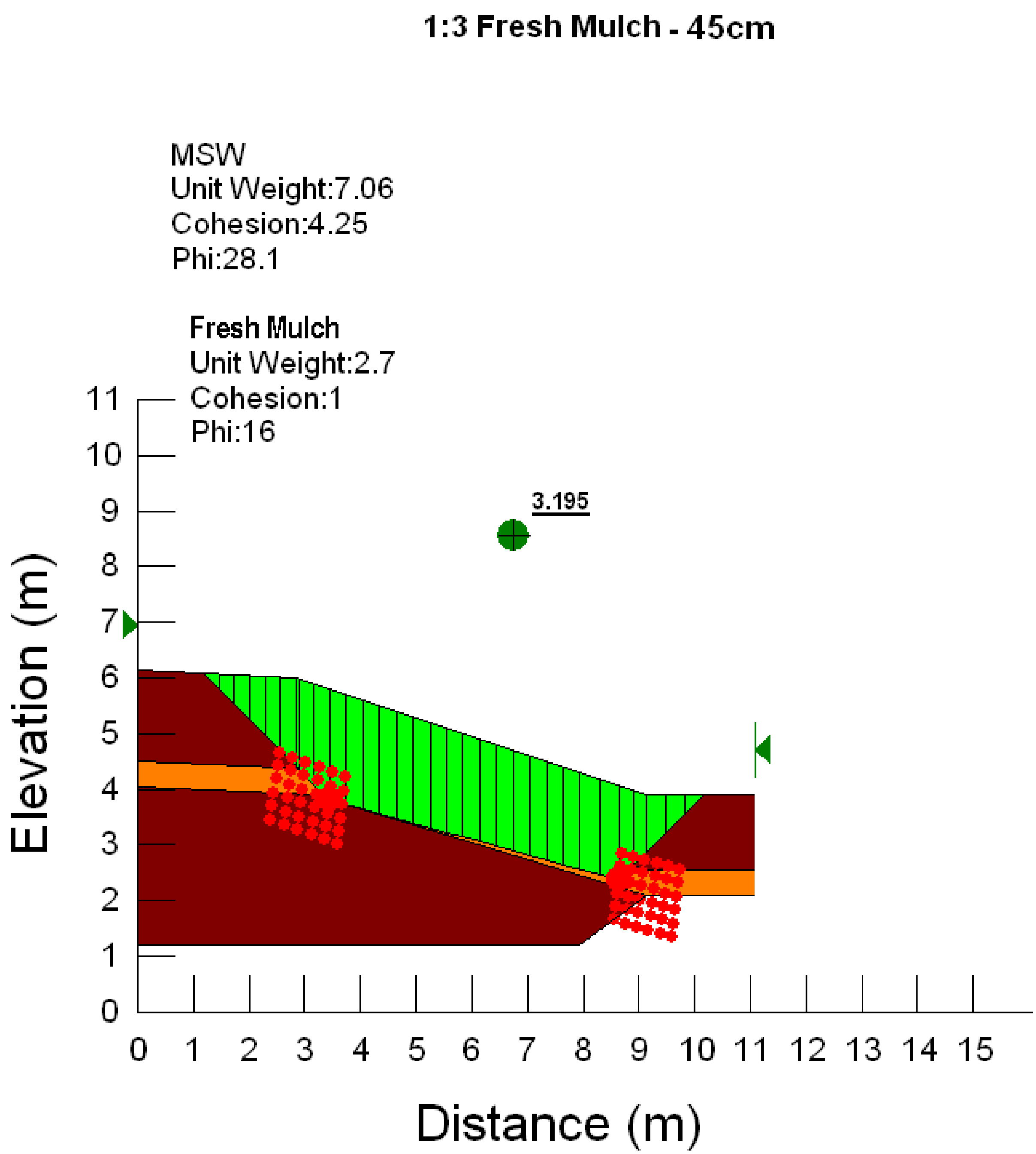

1:3 Fresh Mix-30cm
MSW
Unit Weight:7.06
Cohesion:4.25
Phi:28.1
Fresh Mix
Unit Weight: 5.6
Cohesion:1
Phi:15
3.098
Elevation (m)
Distance (m)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

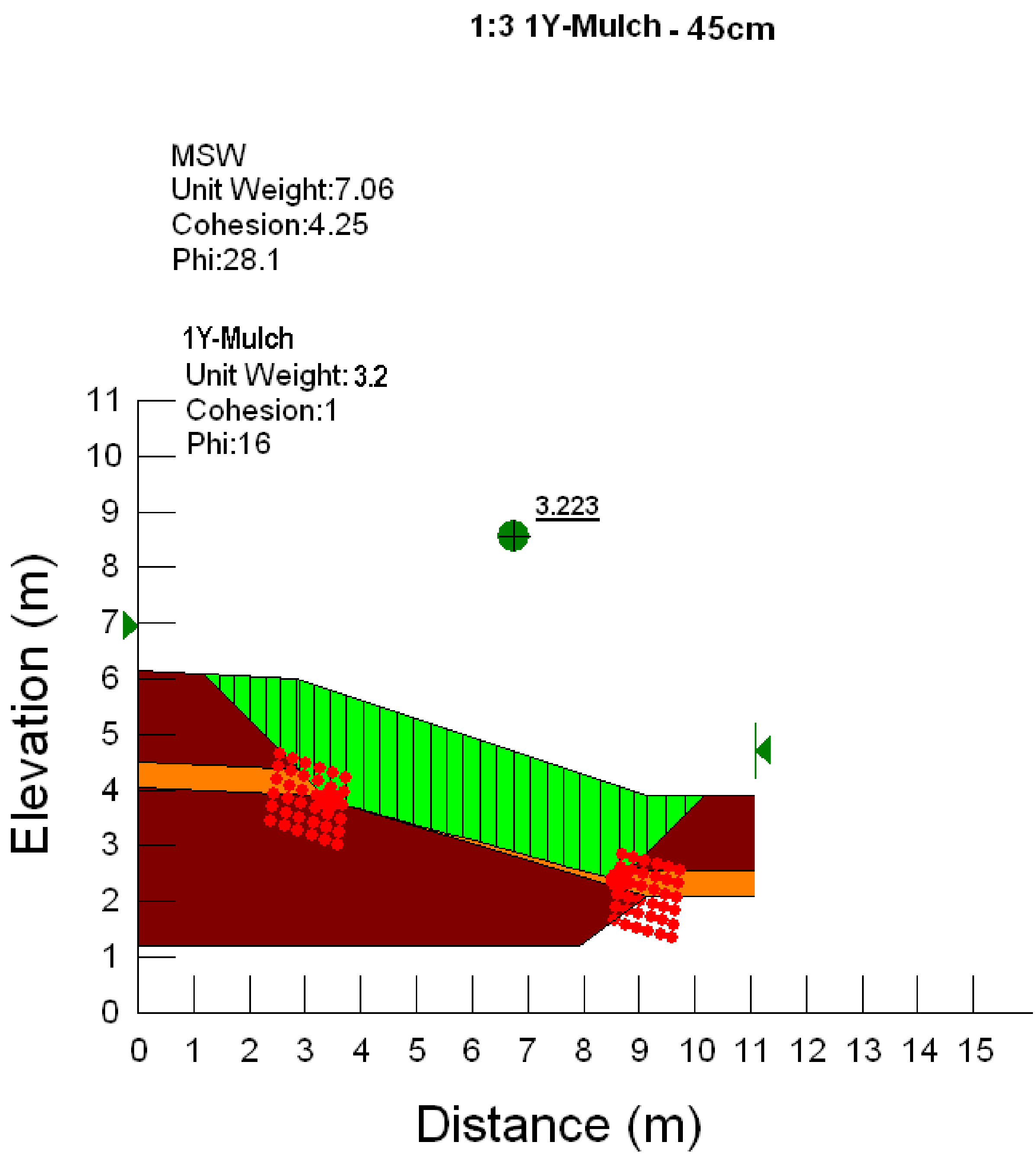

1:3 1Y-Mix-30cm
MSW
Unit Weight:7.06
Cohesion:4.25
Phi:28.1
1Y-Mix
Unit Weight: 6.7
Cohesion:0
Phi:12
2.658
Elevation (m)
Distance (m)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15


1:3 3Y-Mix-30cm
MSW
Unit Weight:7.06
Cohesion:4.25
Phi:28.1
3Y-Mix
Unit Weight: 9.4
Cohesion:0
Phi:11
2.557
Elevation (m)
Distance (m)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

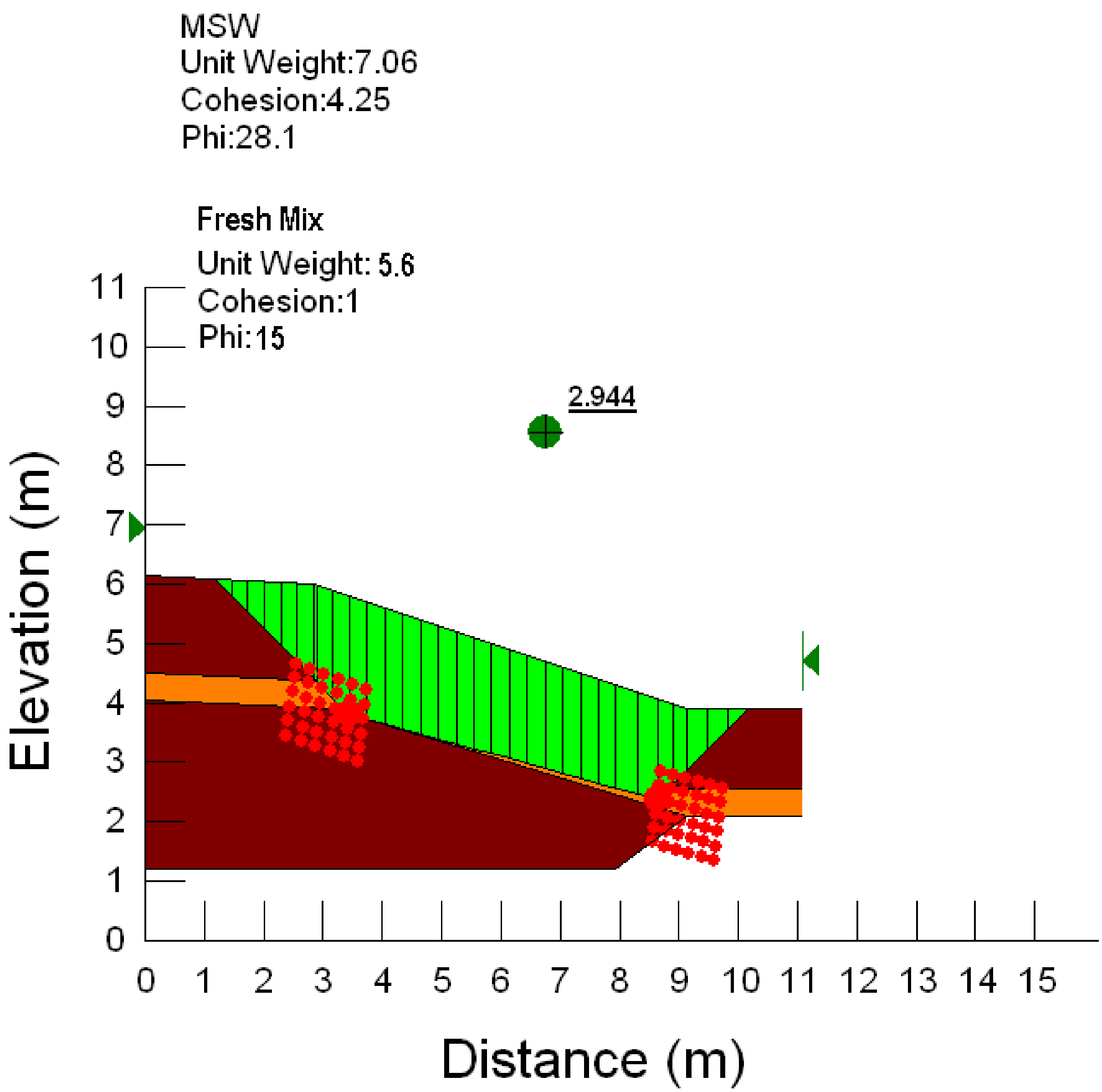

1:3 Soil-30cm
MSW
Unit Weight:7.06
Cohesion:4.25
Phi:28.1
Soil
Unit Weight: 12
Cohesion: 0
Phi: 10
2.307
Elevation (m)
Distance (m)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

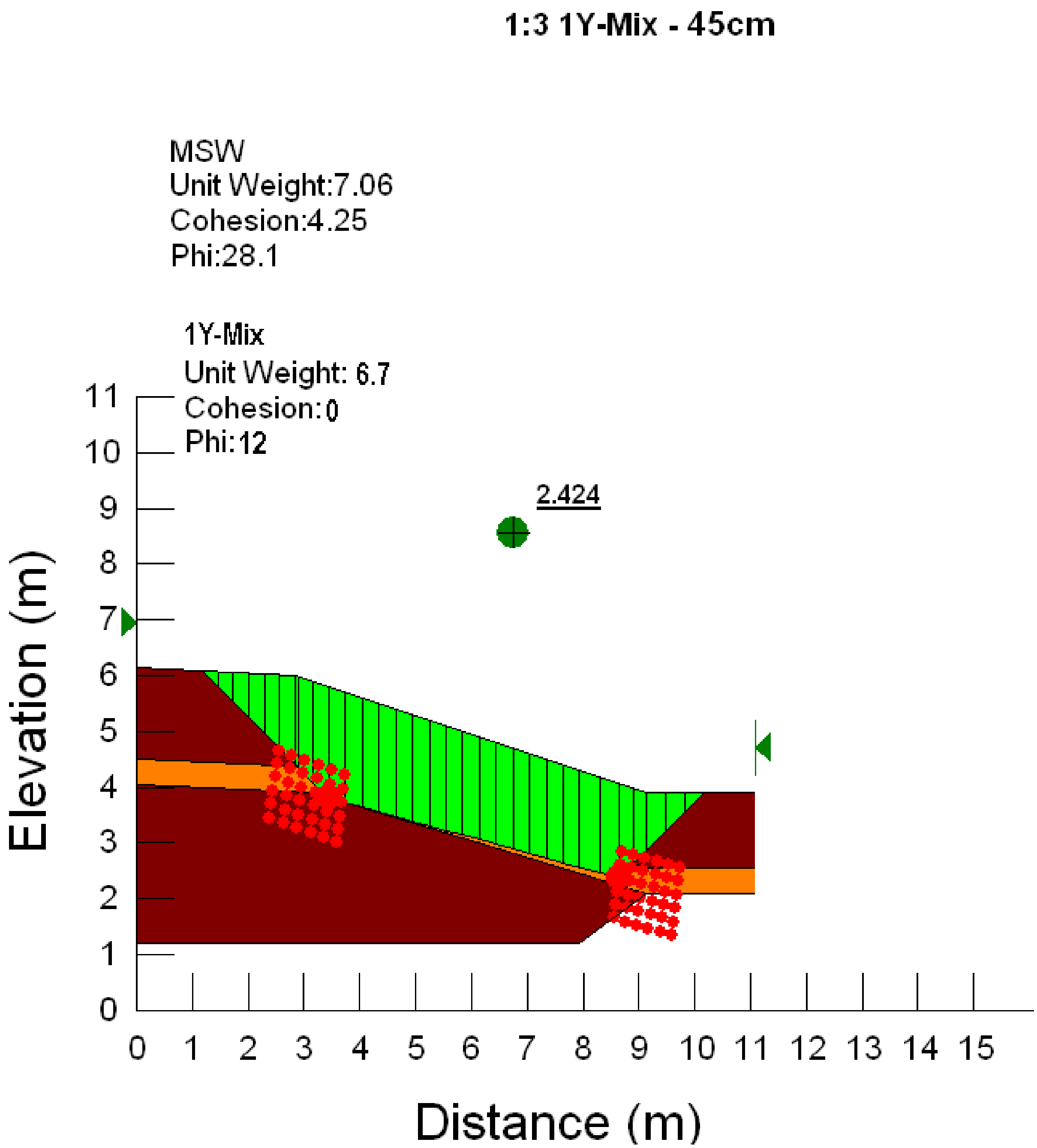
Block Failure (Slope 1:3 / Cover Depth = 45cm)

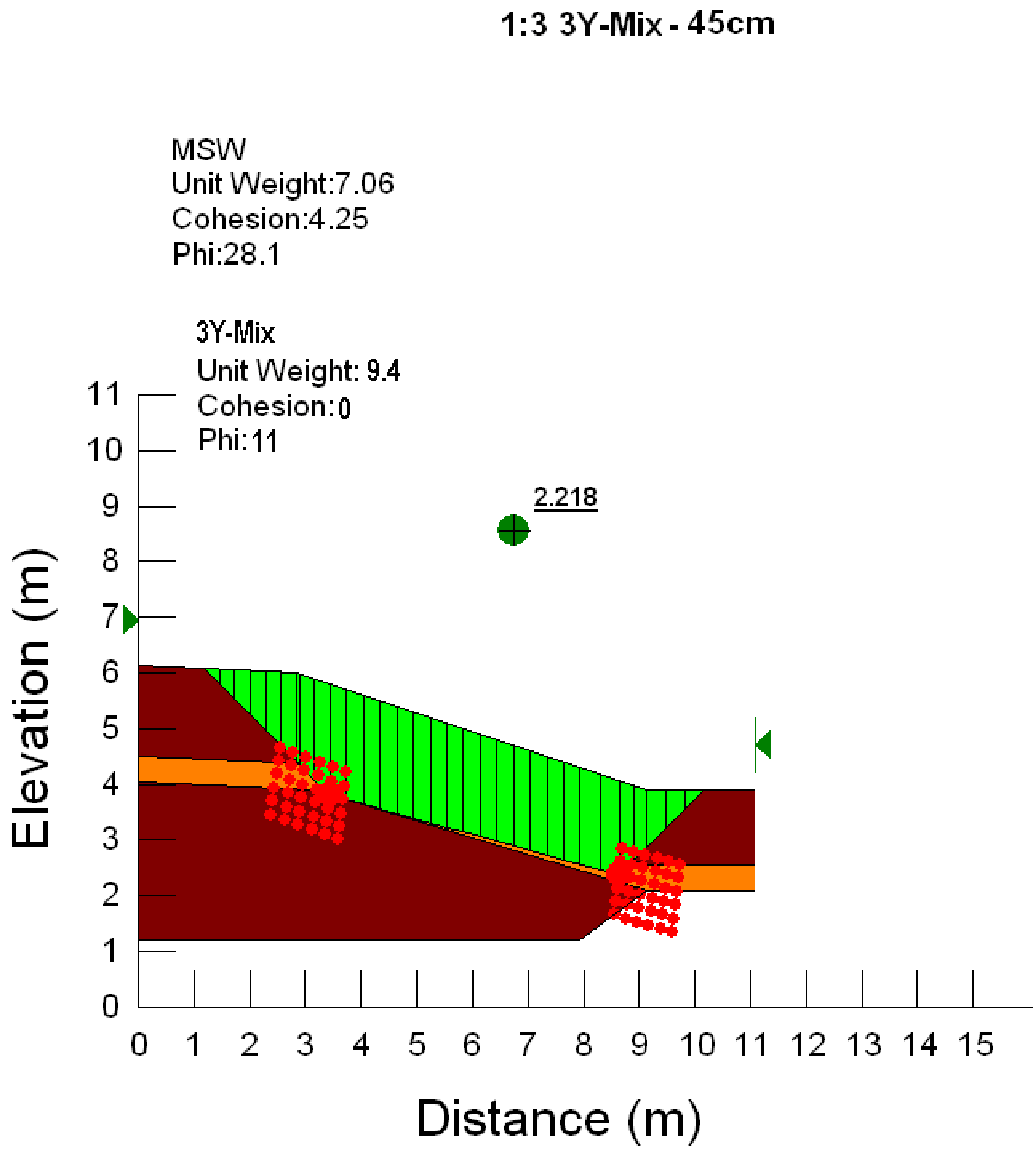



1:3 1Y-Mulch - 45cm
MSW
Unit Weight:7.06
Cohesion:4.25
Phi:28.1
1Y-Mulch
Unit Weight: 3.2
Cohesion:1
Phi:16
3.223
Elevation (m)
Distance (m)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

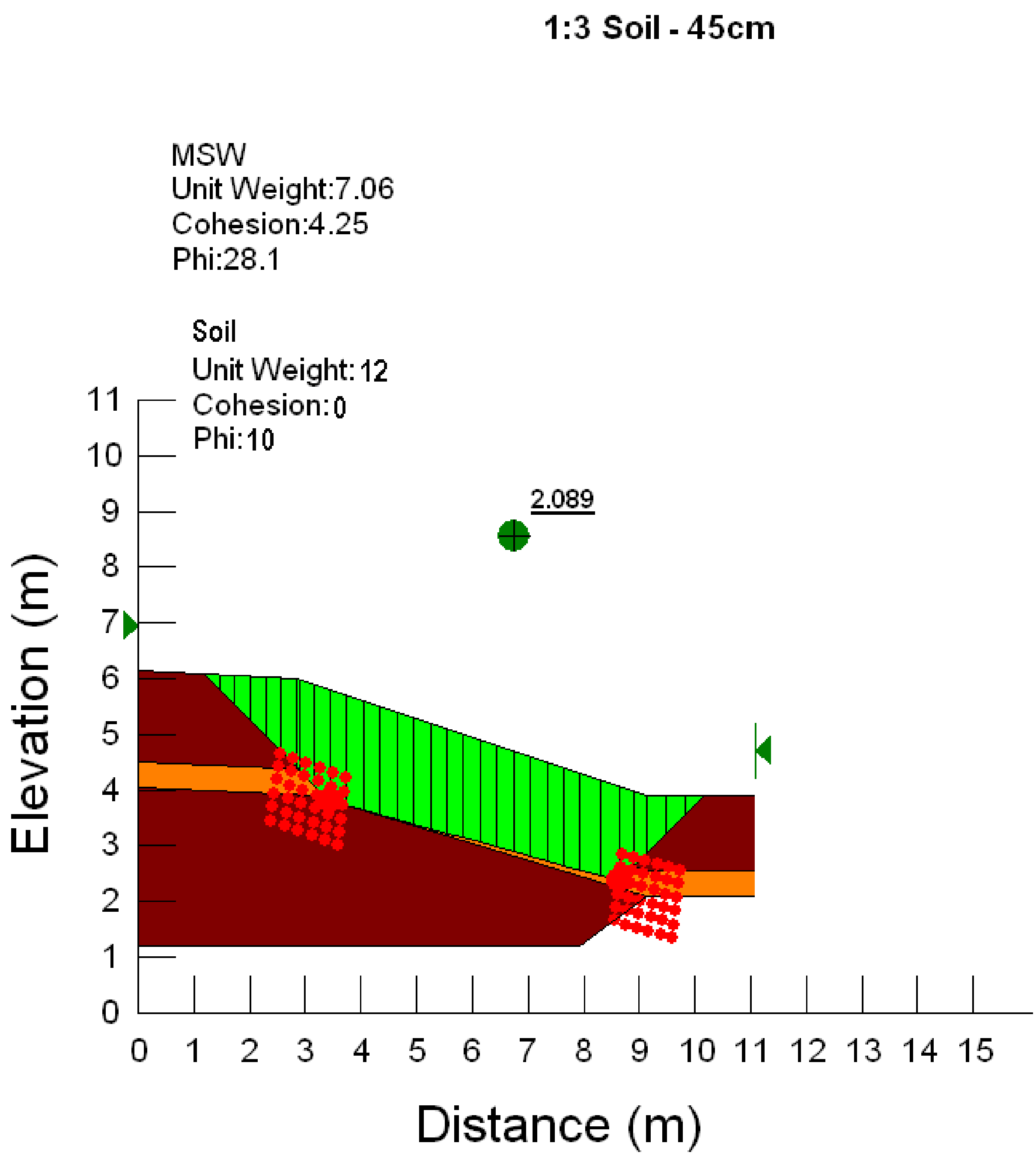
1:3 Fresh Mix - 45cm



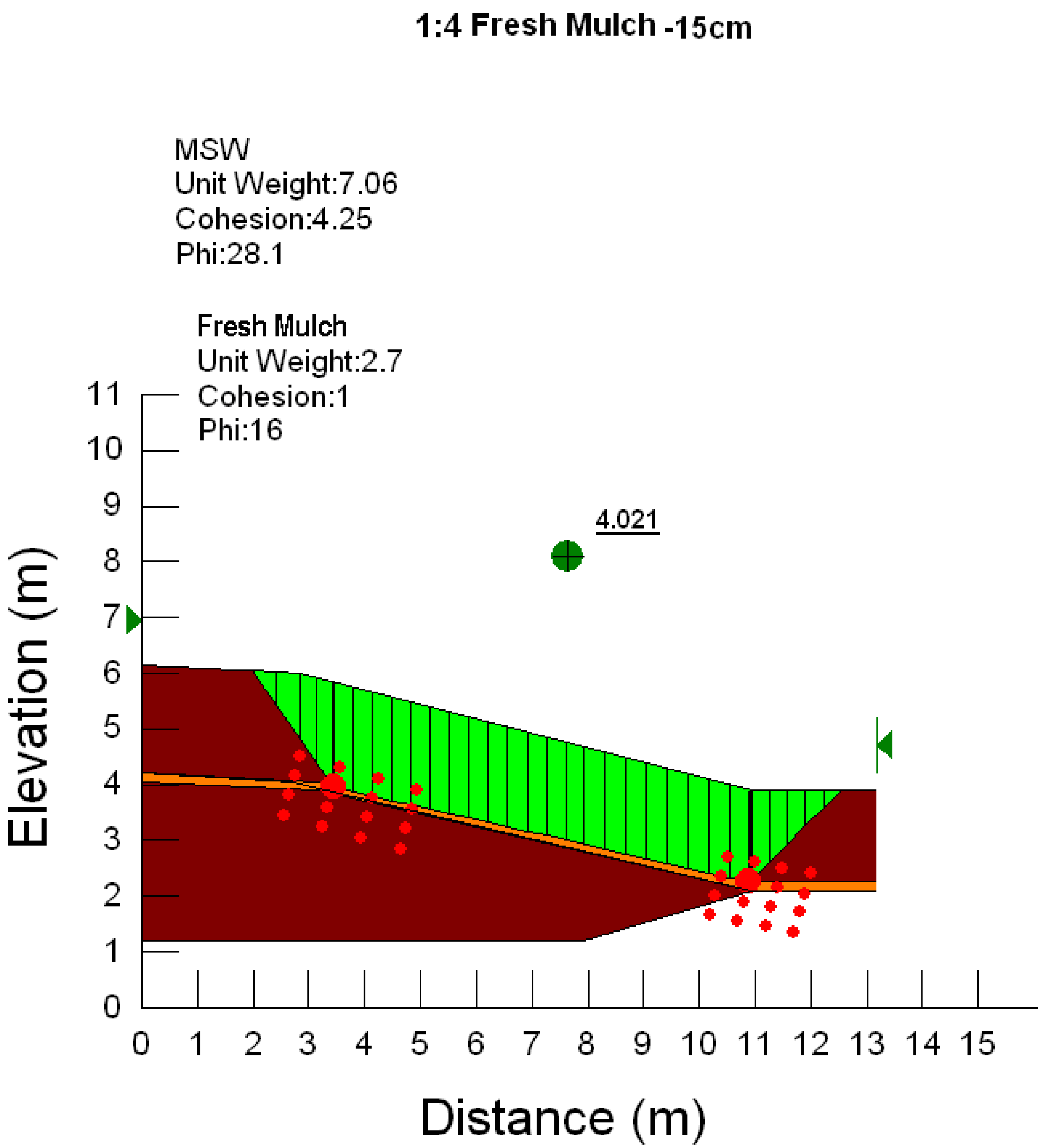

1:3 1Y-Mix - 45cm
MSW
Unit Weight:7.06
Cohesion:4.25
Phi:28.1
1Y-Mix
Unit Weight: 6.7
Cohesion: 0
Phi: 12
2.424
Elevation (m)
Distance (m)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15



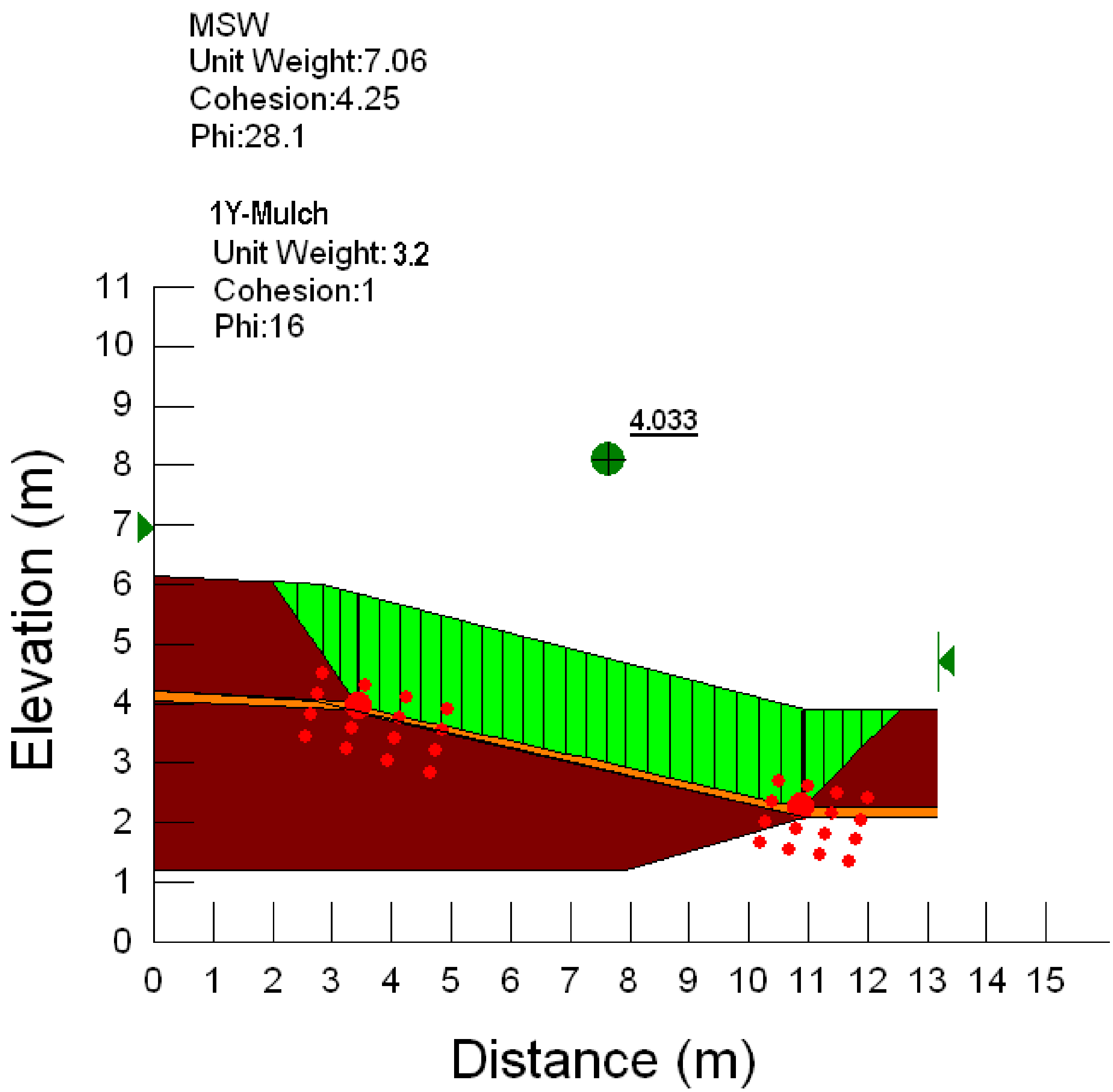
1:3 3Y-Mix - 45cm
MSW
Unit Weight:7.06
Cohesion:4.25
Phi:28.1
3Y-Mix
Unit Weight: 9.4
Cohesion:0
Phi:11
2.218
Elevation (m)
Distance (m)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15


1:3 Soil - 45cm
MSW
Unit Weight:7.06
Cohesion:4.25
Phi:28.1
Soil
Unit Weight:12
Cohesion:0
Phi:10
2.089
Elevation (m)
Distance (m)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

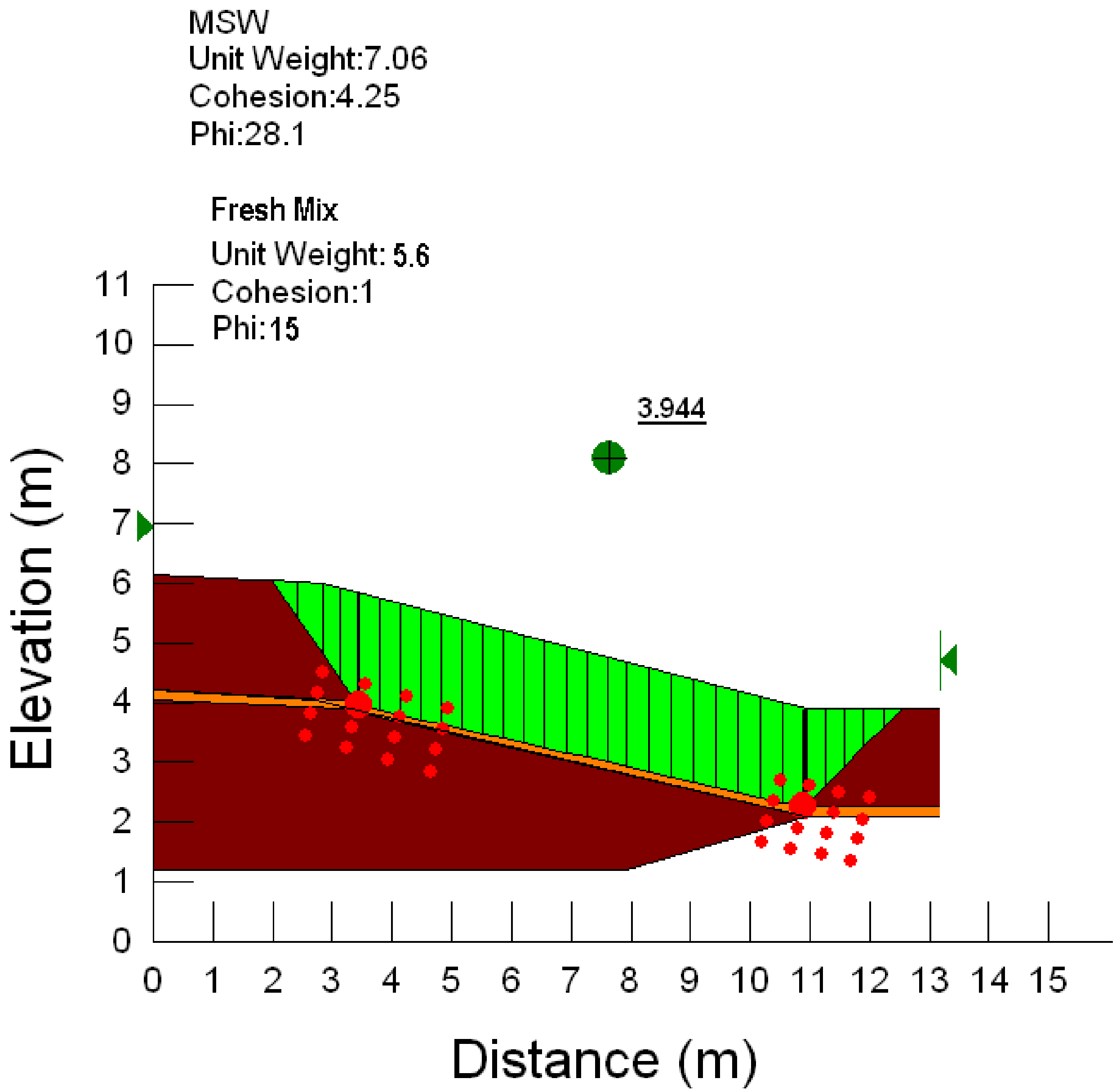
Block Failure (Slope 1:4 / Cover Depth = 15cm)

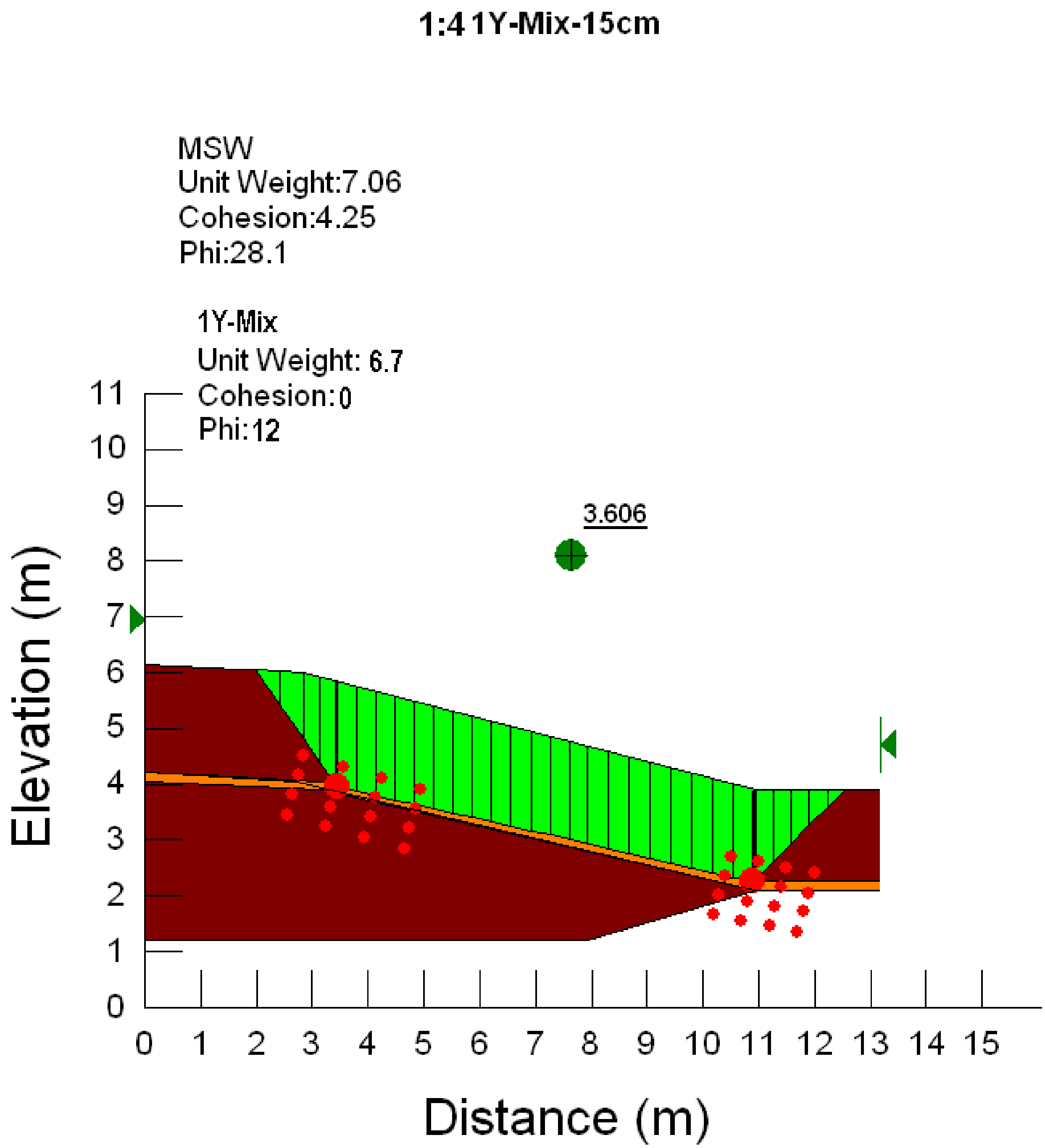


1:4 1Y-Mulch-15cm



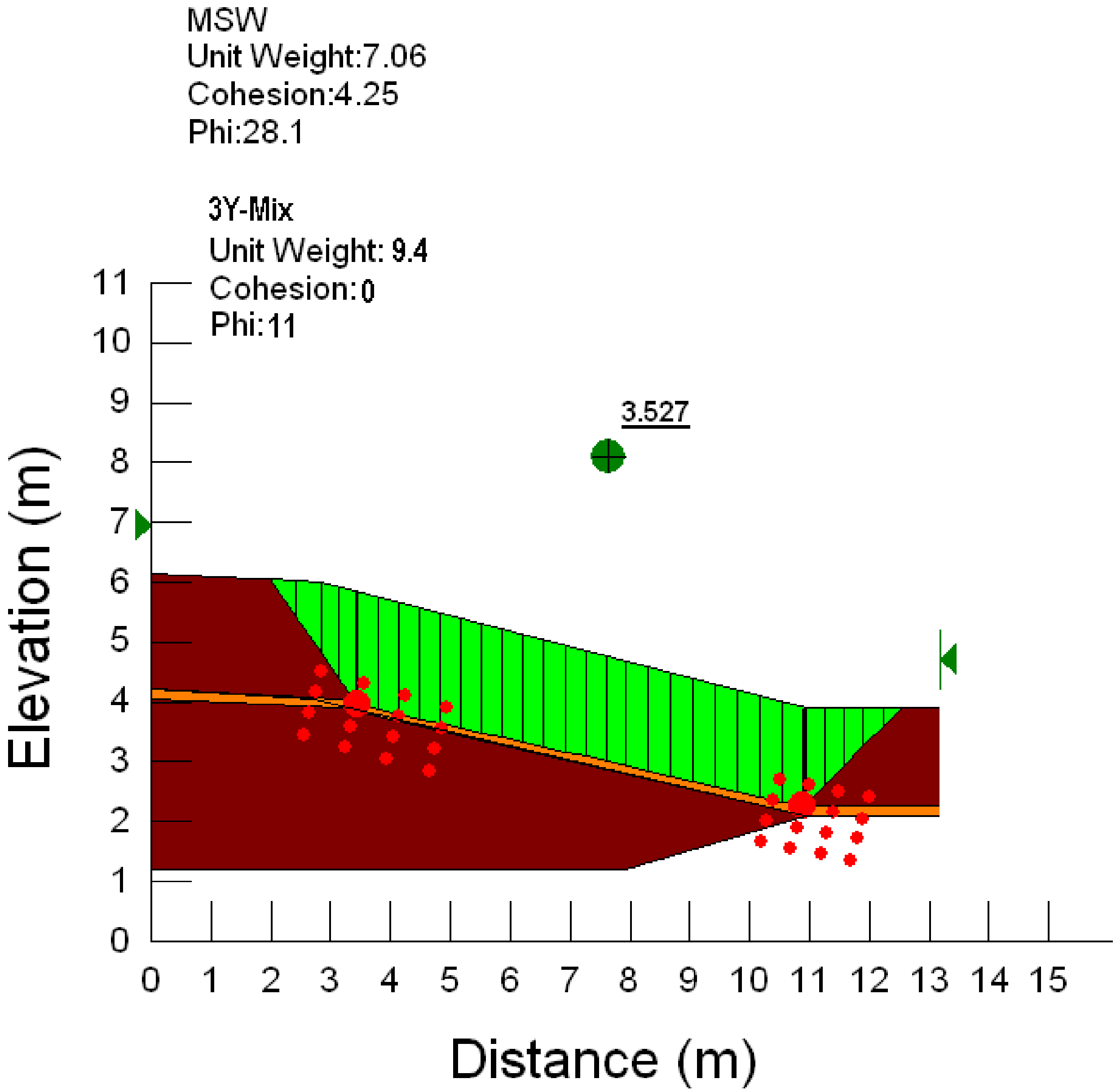
1:4 Fresh Mix-15cm

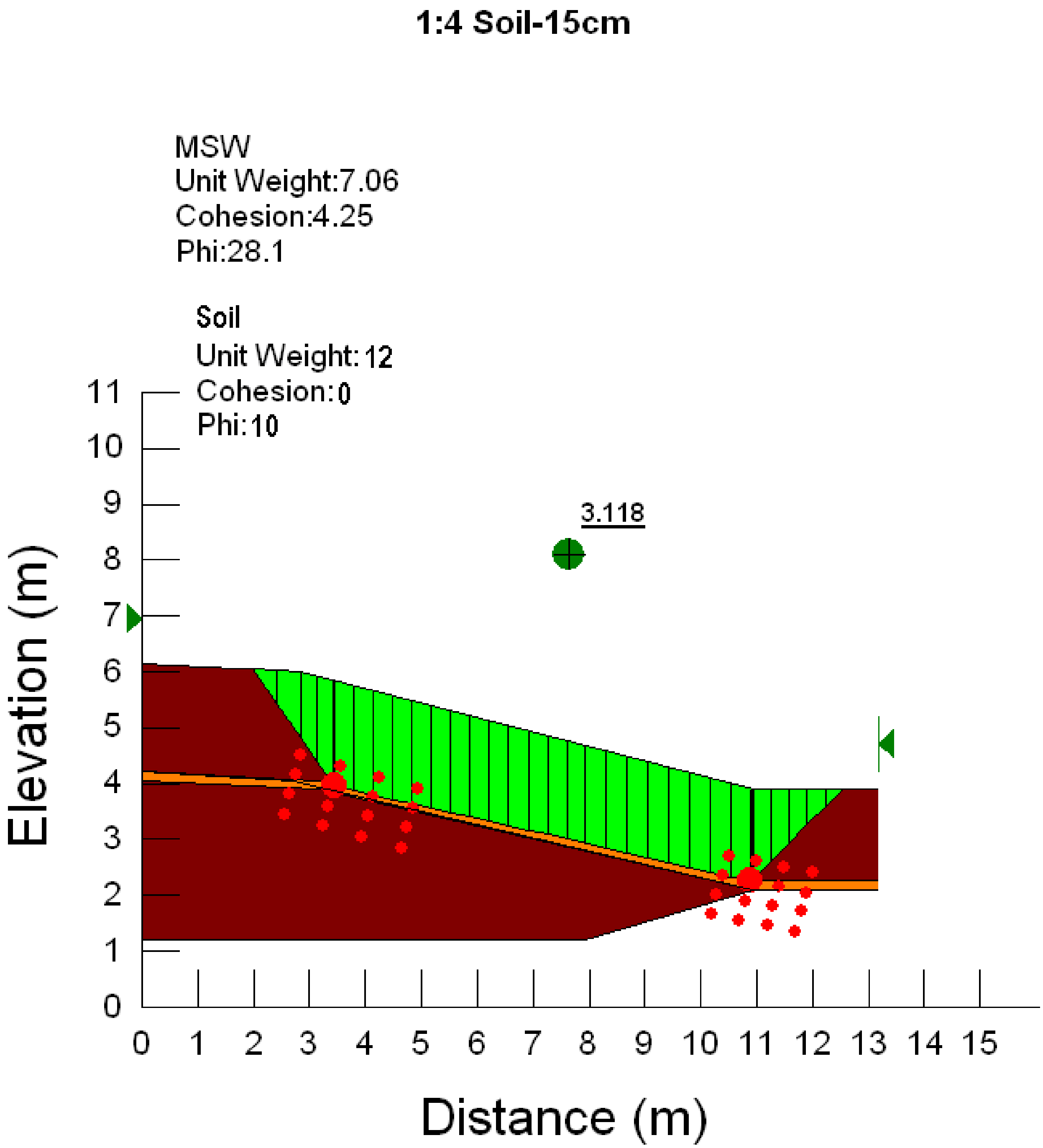




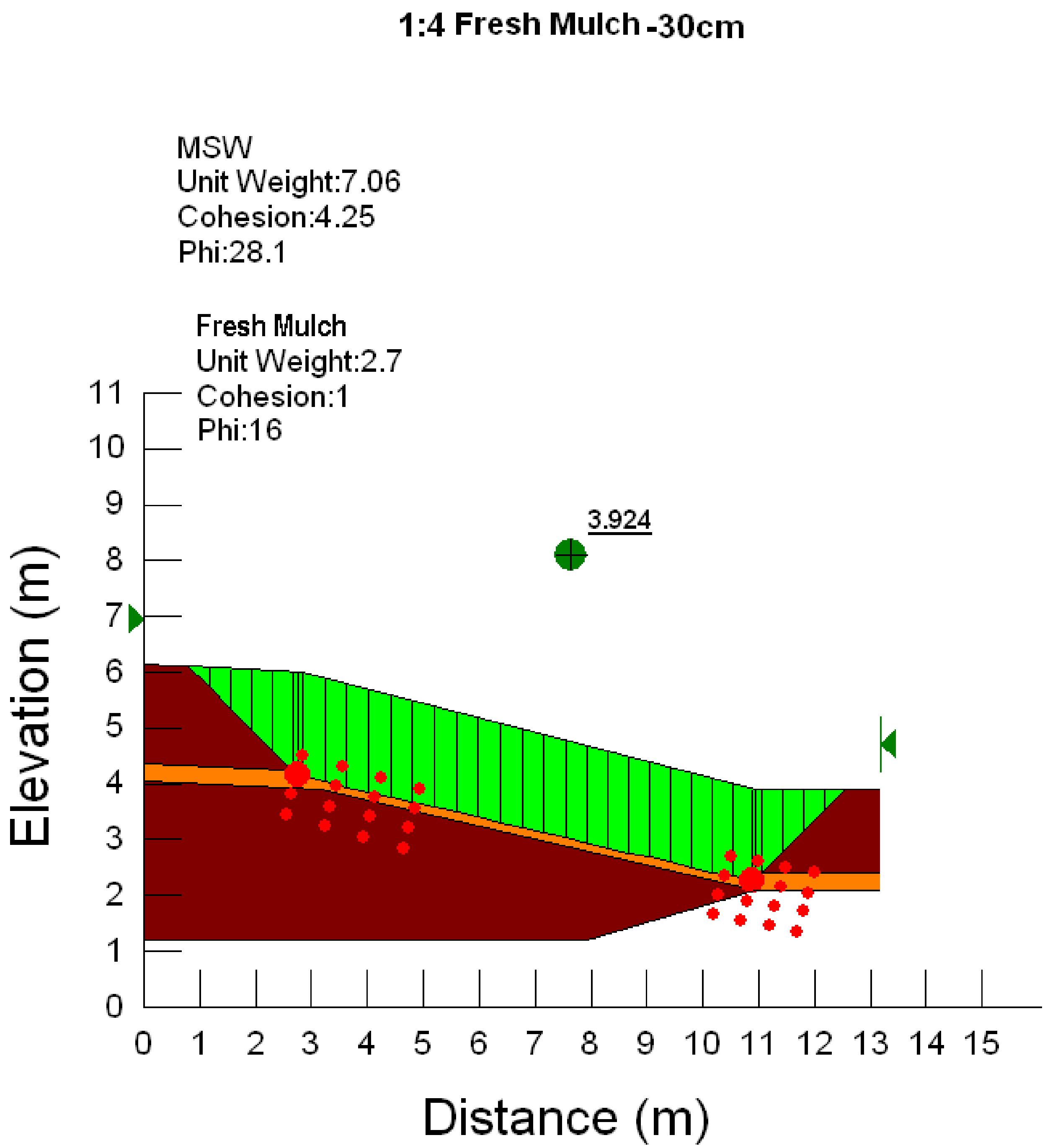
1:4 1Y-Mix-15cm
MSW
Unit Weight:7.06
Cohesion:4.25
Phi:28.1
1Y-Mix
Unit Weight: 6.7
Cohesion:0
Phi:12
3.606
Elevation (m)
Distance (m)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

1:4 3Y-Mix-15cm

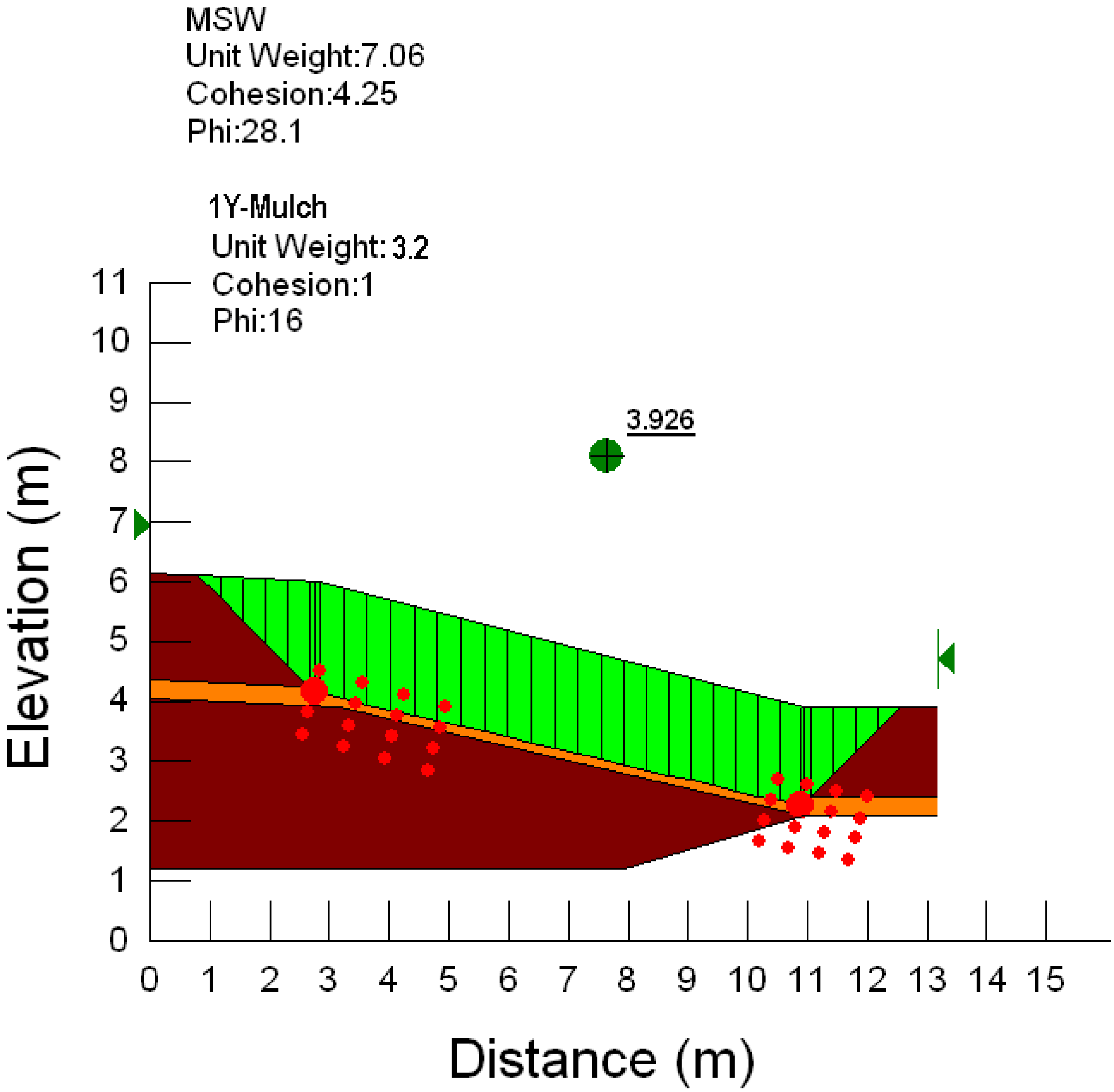


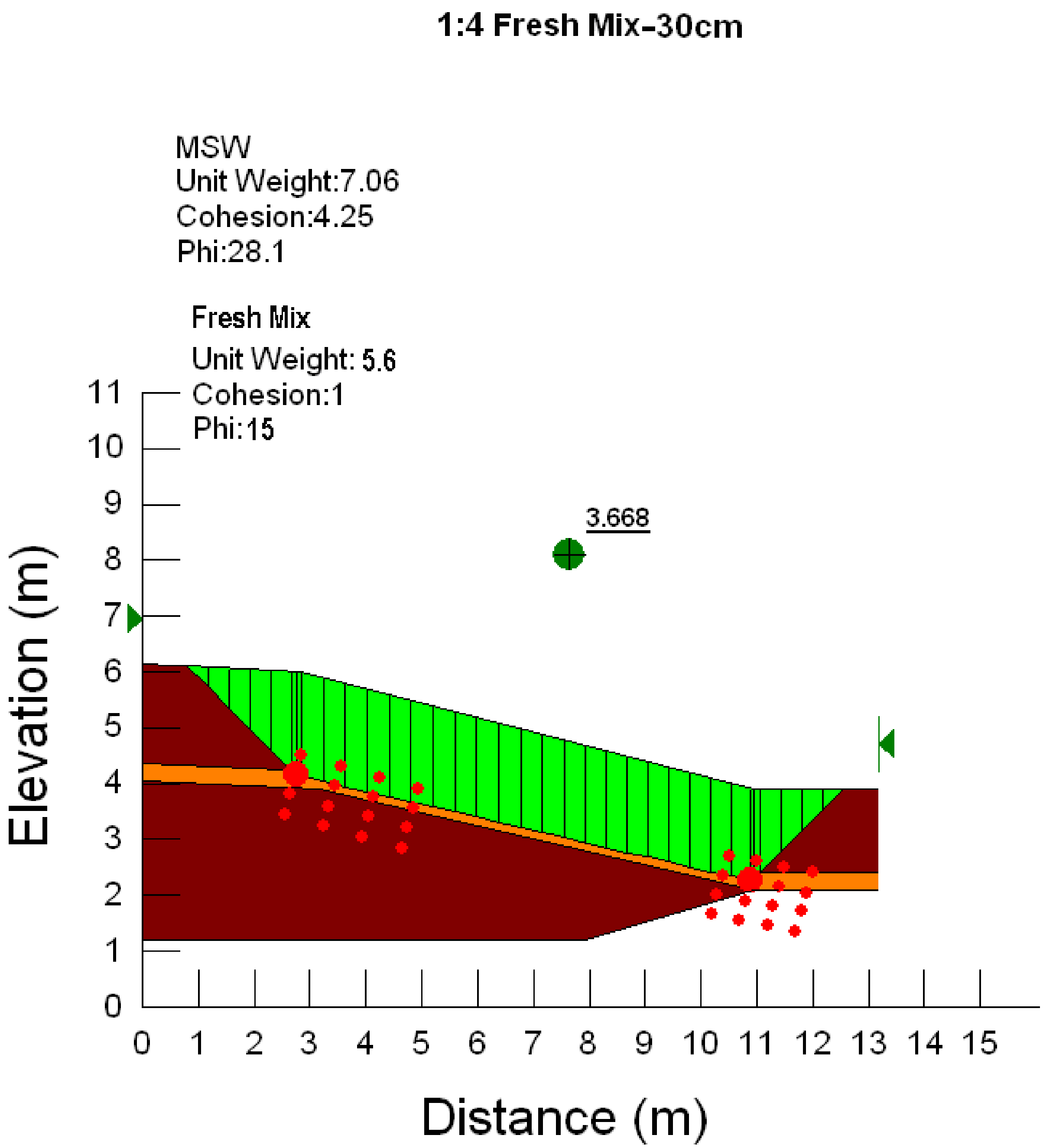

1:4 Soil-15cm
MSW
Unit Weight:7.06
Cohesion:4.25
Phi:28.1
Soil
Unit Weight: 12
Cohesion: 0
Phi: 10
3.118
Elevation (m)
Distance (m)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

Block Failure (Slope 1:4 / Cover Depth = 30cm)

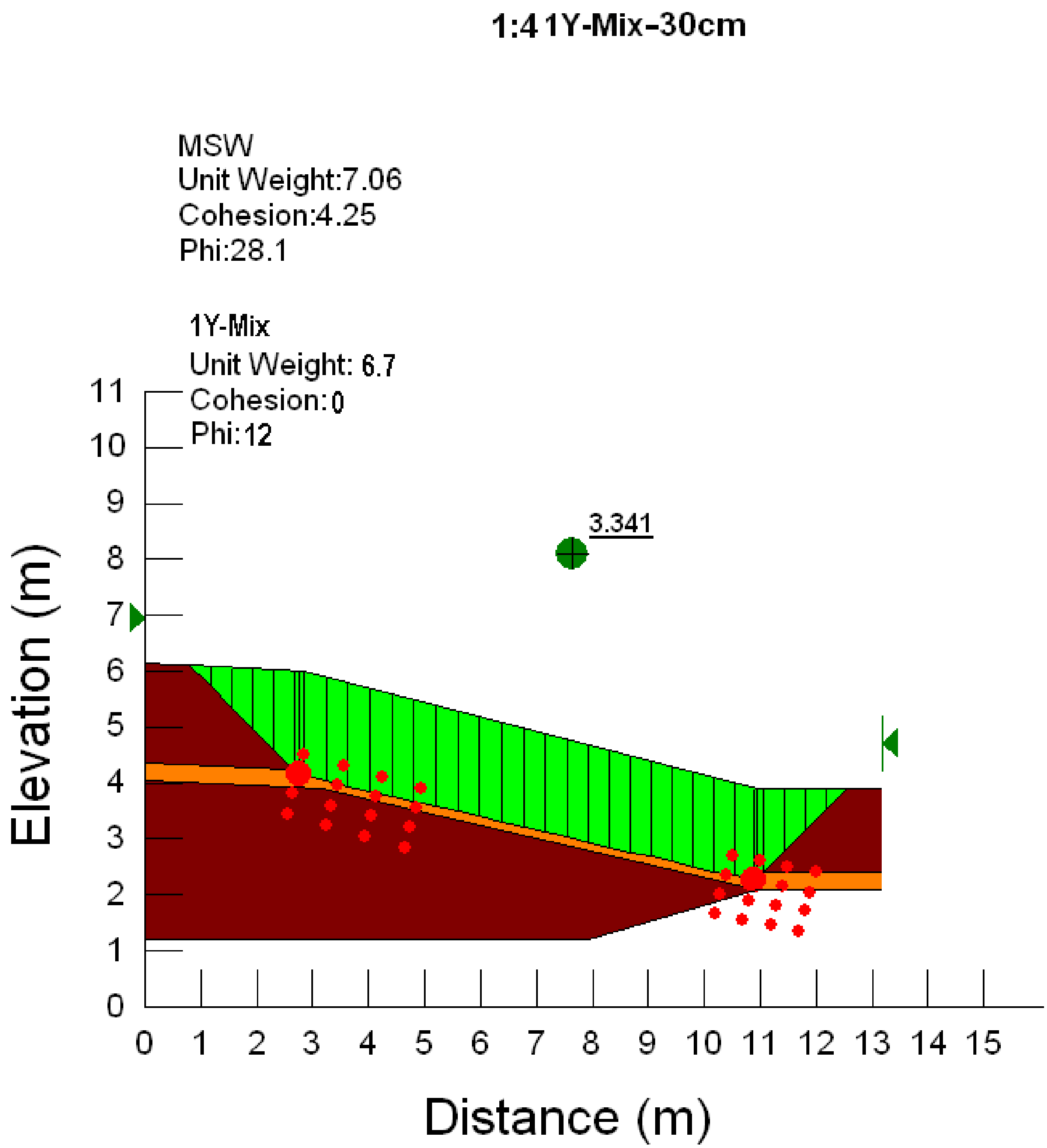


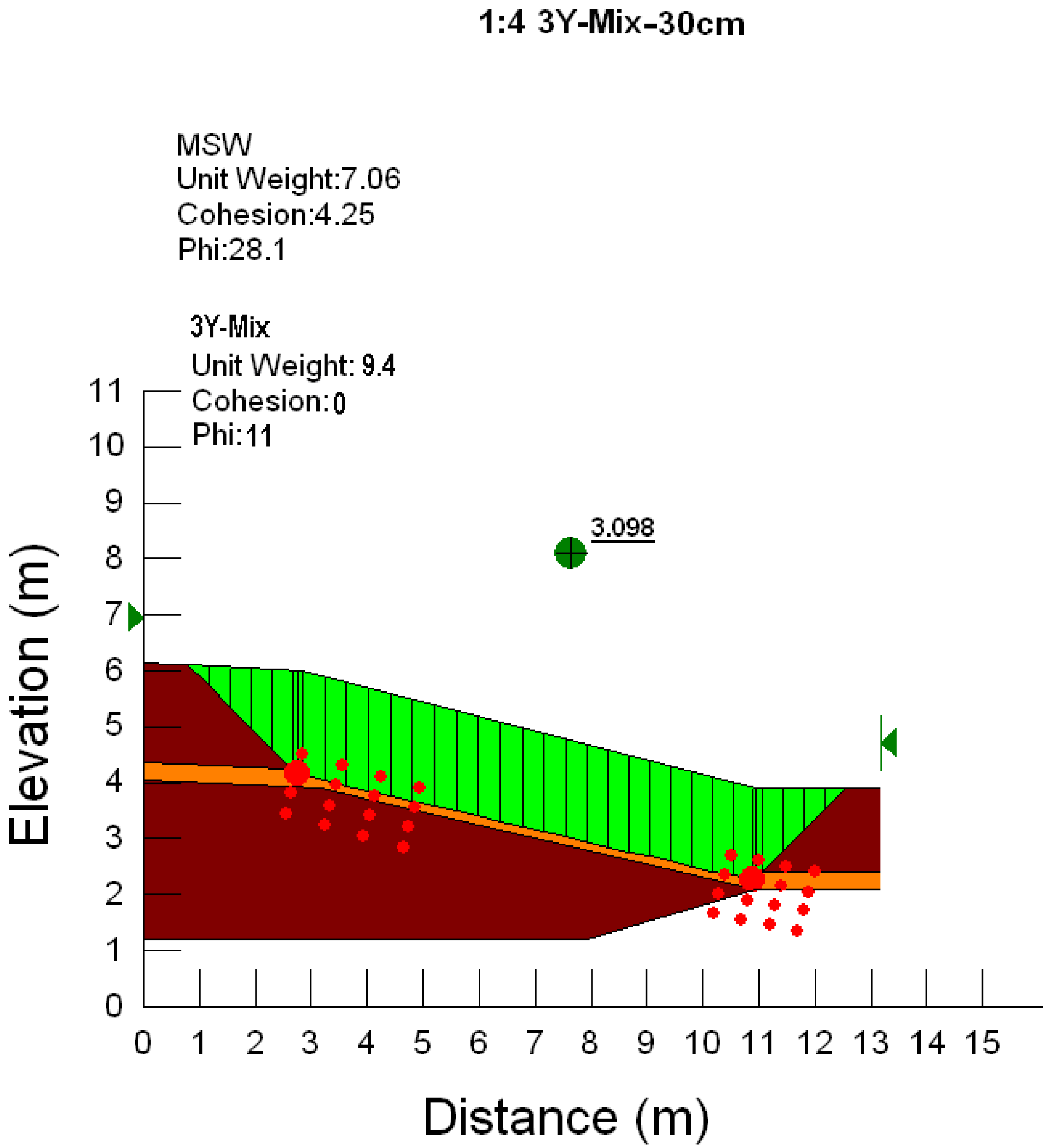
1:4 1Y-Mulch-30cm

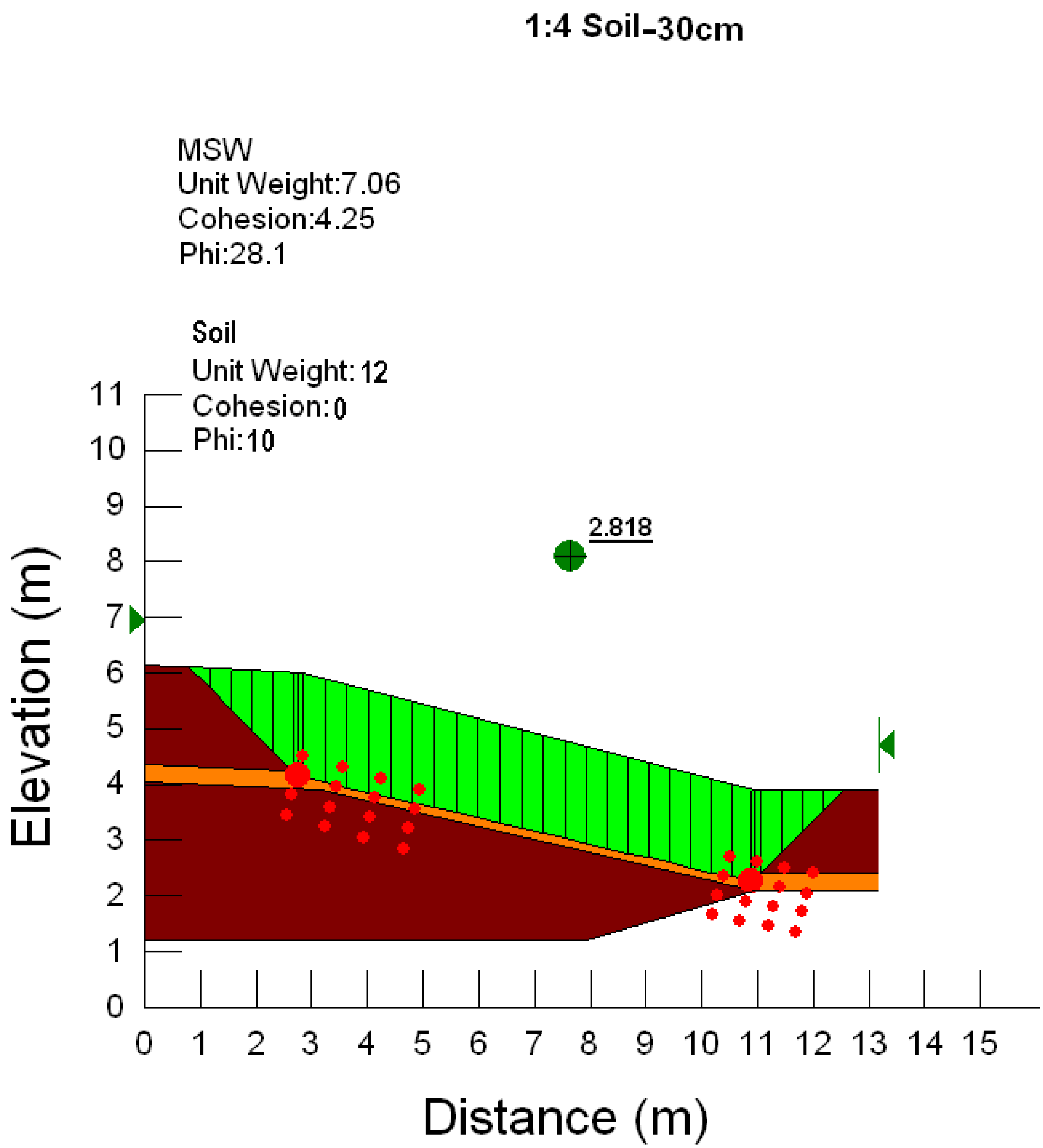




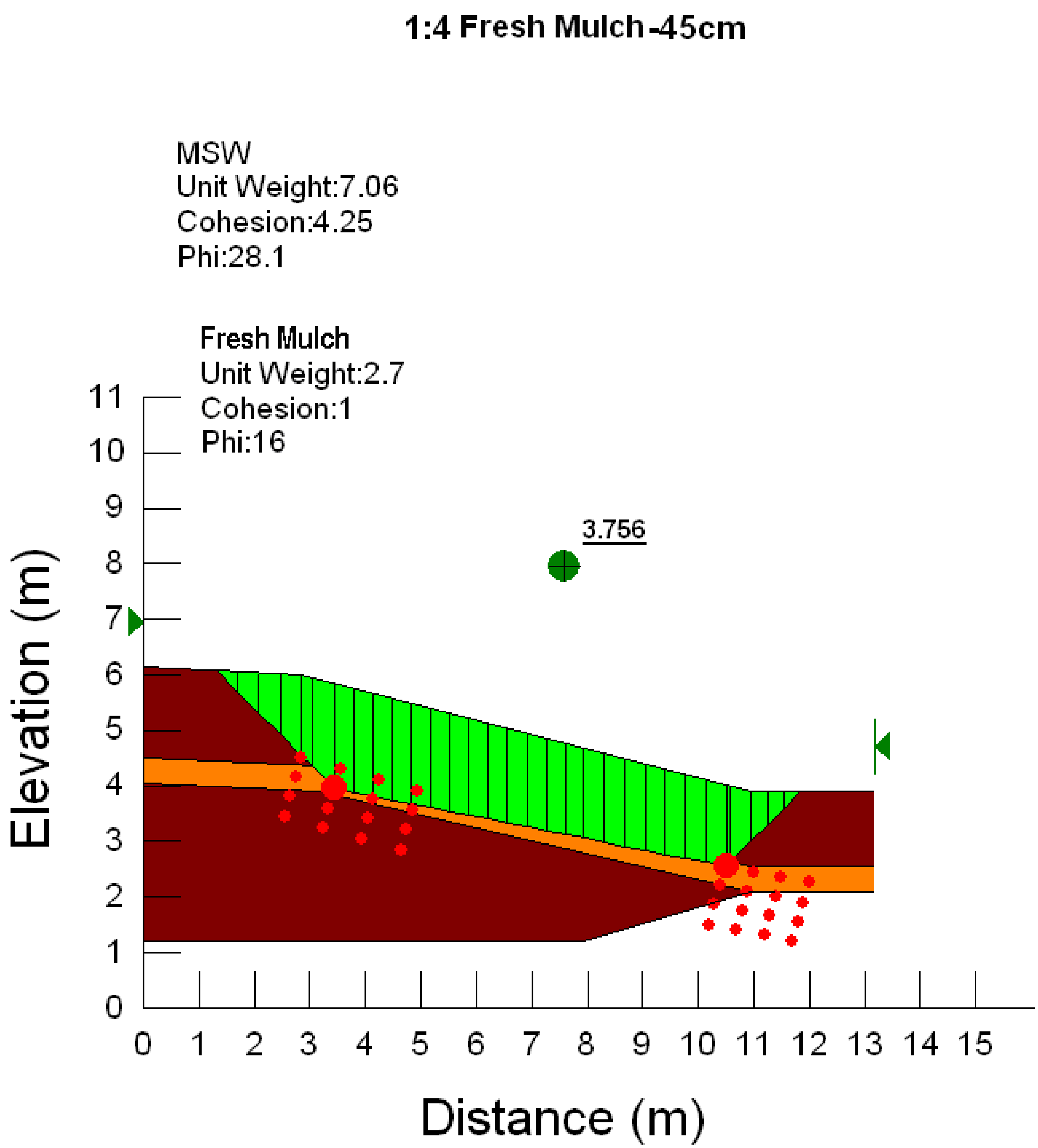
1:4 Fresh Mix-30cm
MSW
Unit Weight:7.06
Cohesion:4.25
Phi:28.1
Fresh Mix
Unit Weight: 5.6
Cohesion:1
Phi:15
3.668
Elevation (m)
Distance (m)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

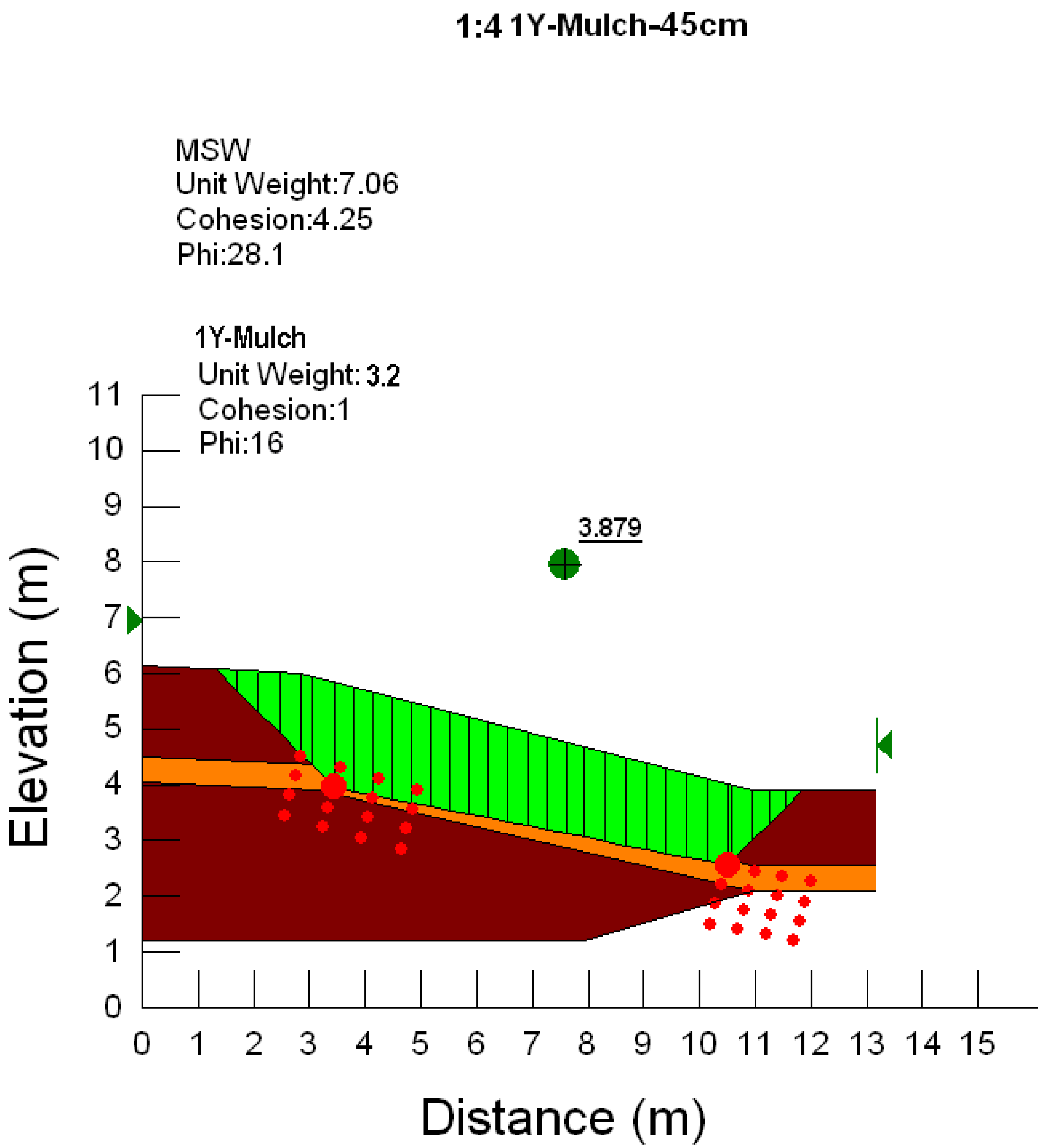

1:4 1Y-Mix-30cm
MSW
Unit Weight:7.06
Cohesion:4.25
Phi:28.1
1Y-Mix
Unit Weight: 6.7
Cohesion:0
Phi:12
3.341
Elevation (m)
Distance (m)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

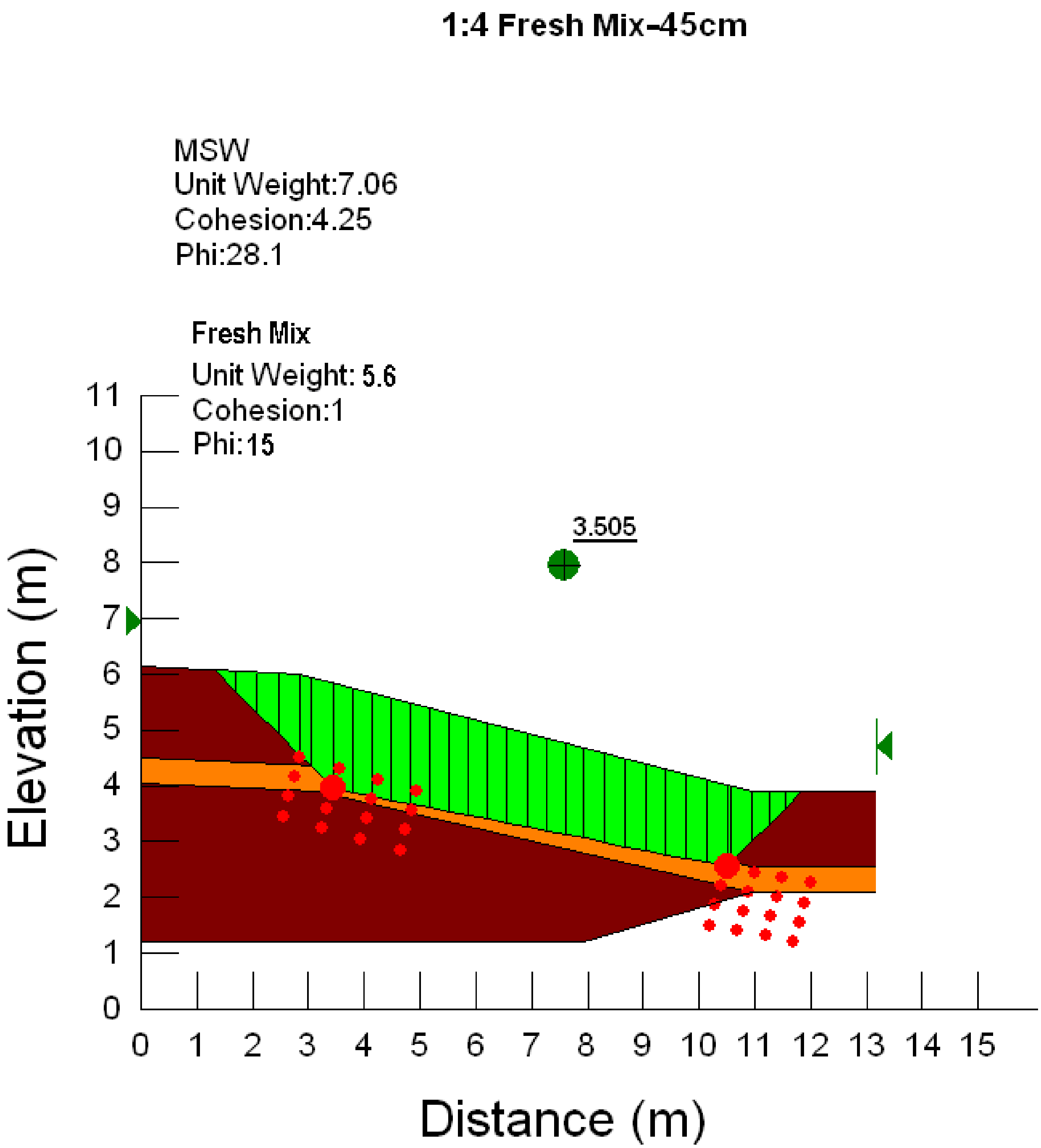

1:4 3Y-Mix-30cm
MSW
Unit Weight:7.06
Cohesion:4.25
Phi:28.1
3Y-Mix
Unit Weight: 9.4
Cohesion:0
Phi:11
3.098
Elevation (m)
Distance (m)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15


1:4 Soil-30cm
MSW
Unit Weight:7.06
Cohesion:4.25
Phi:28.1
Soil
Unit Weight: 12
Cohesion: 0
Phi: 10
2.818
Elevation (m)
Distance (m)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

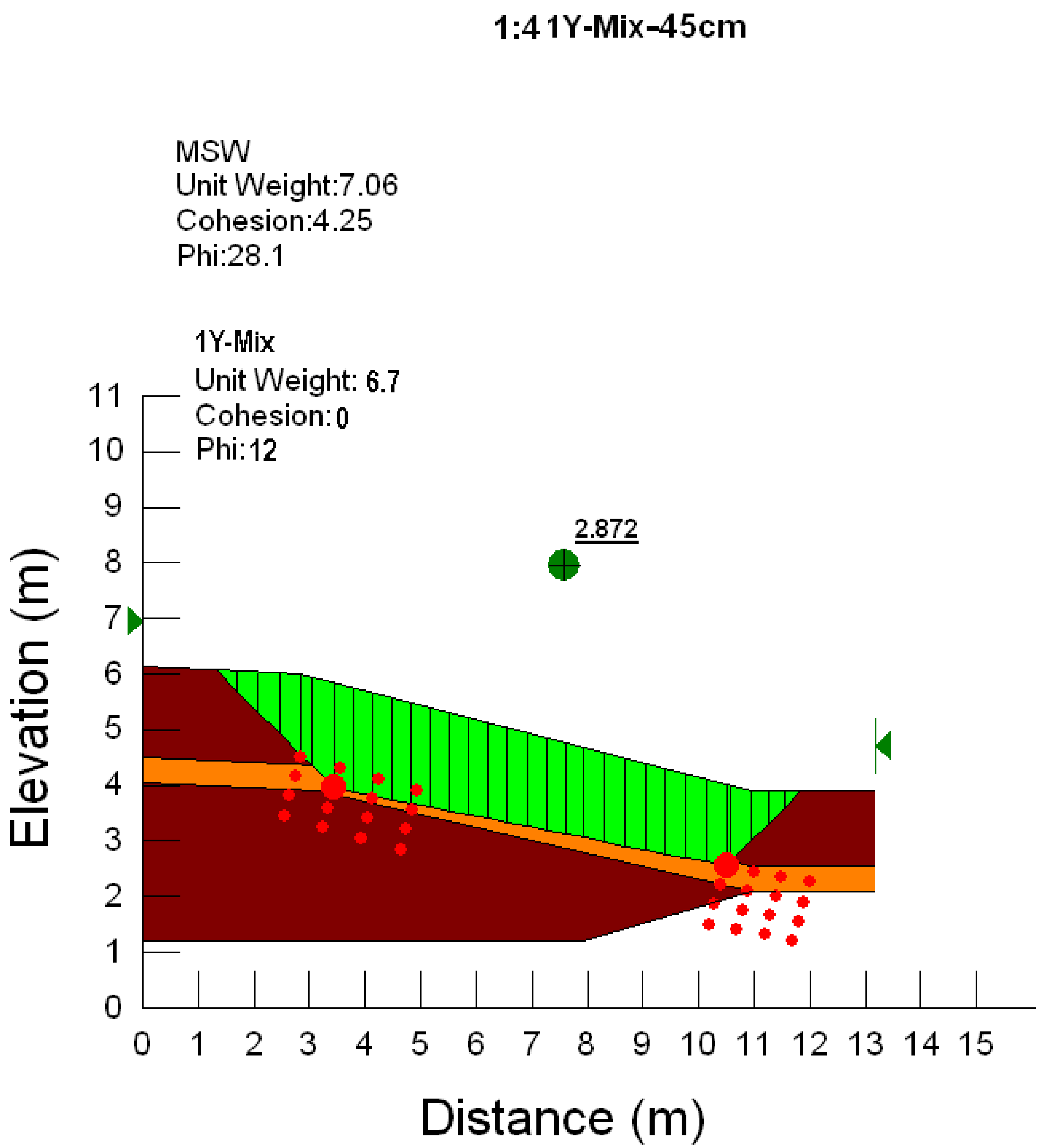
Block Failure (Slope 1:4 / Cover Depth = 45cm)

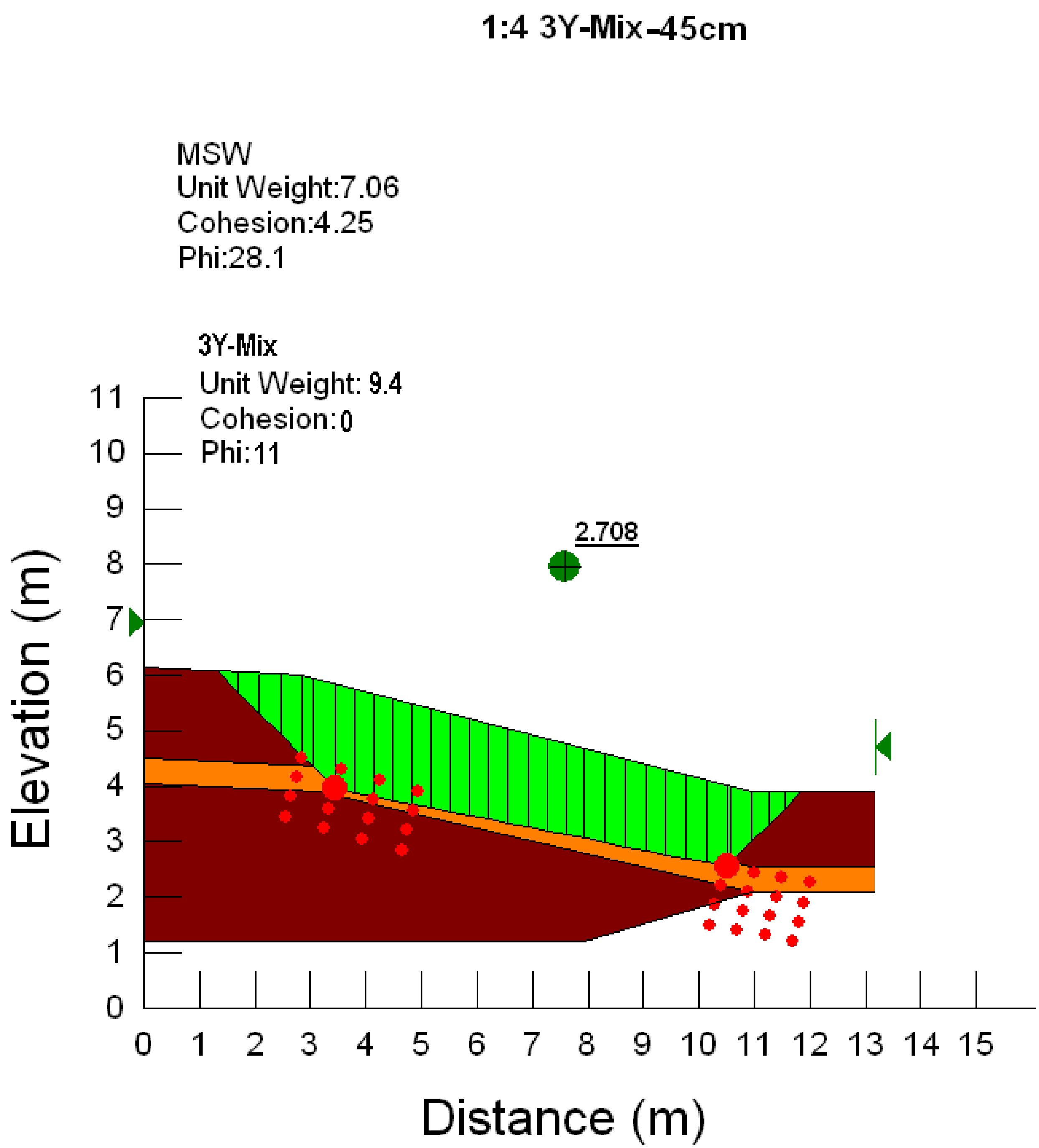


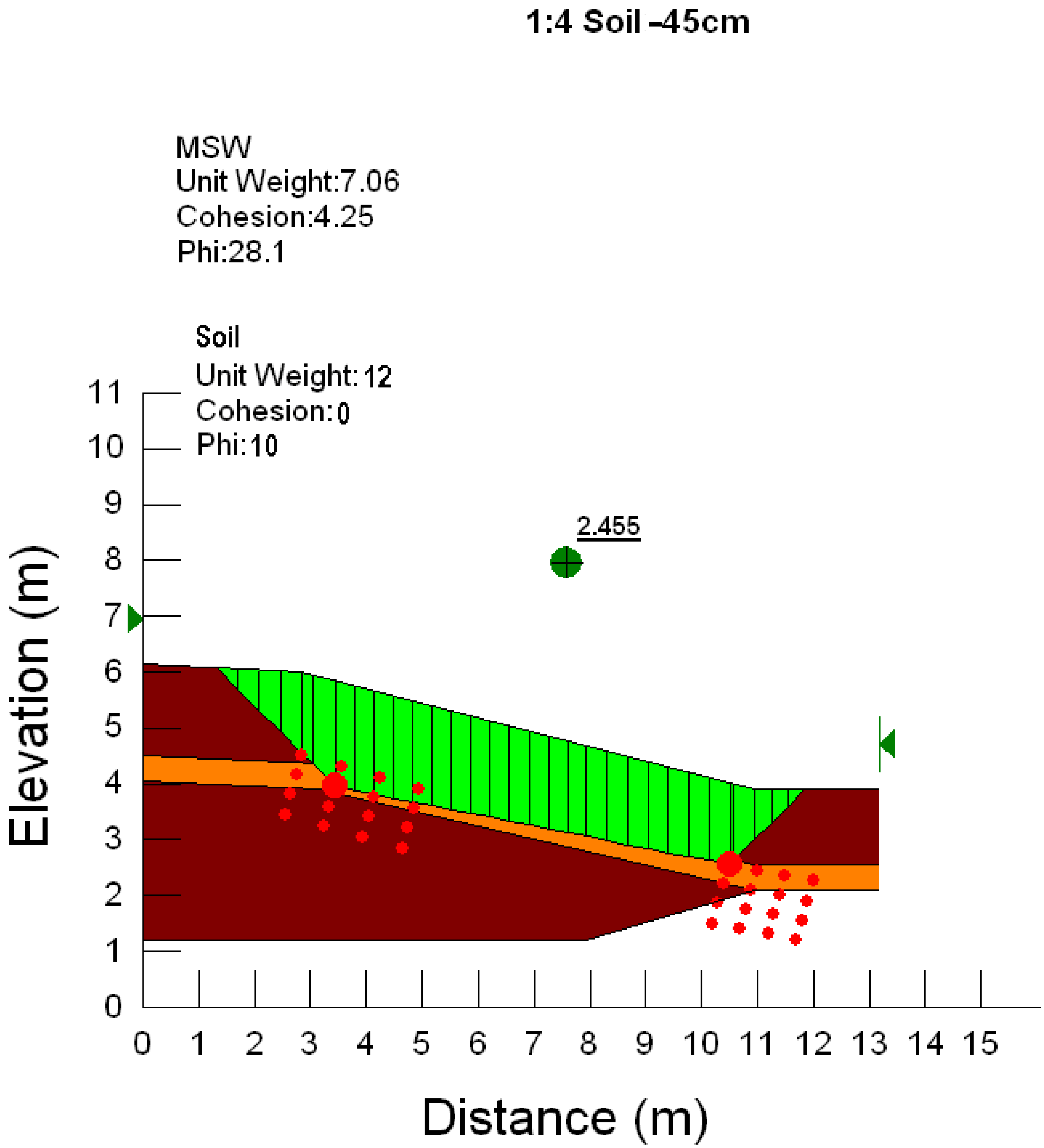

1:4 1Y-Mulch-45cm
MSW
Unit Weight:7.06
Cohesion:4.25
Phi:28.1
1Y-Mulch
Unit Weight: 3.2
Cohesion:1
Phi:16
3.879
Elevation (m)
Distance (m)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15



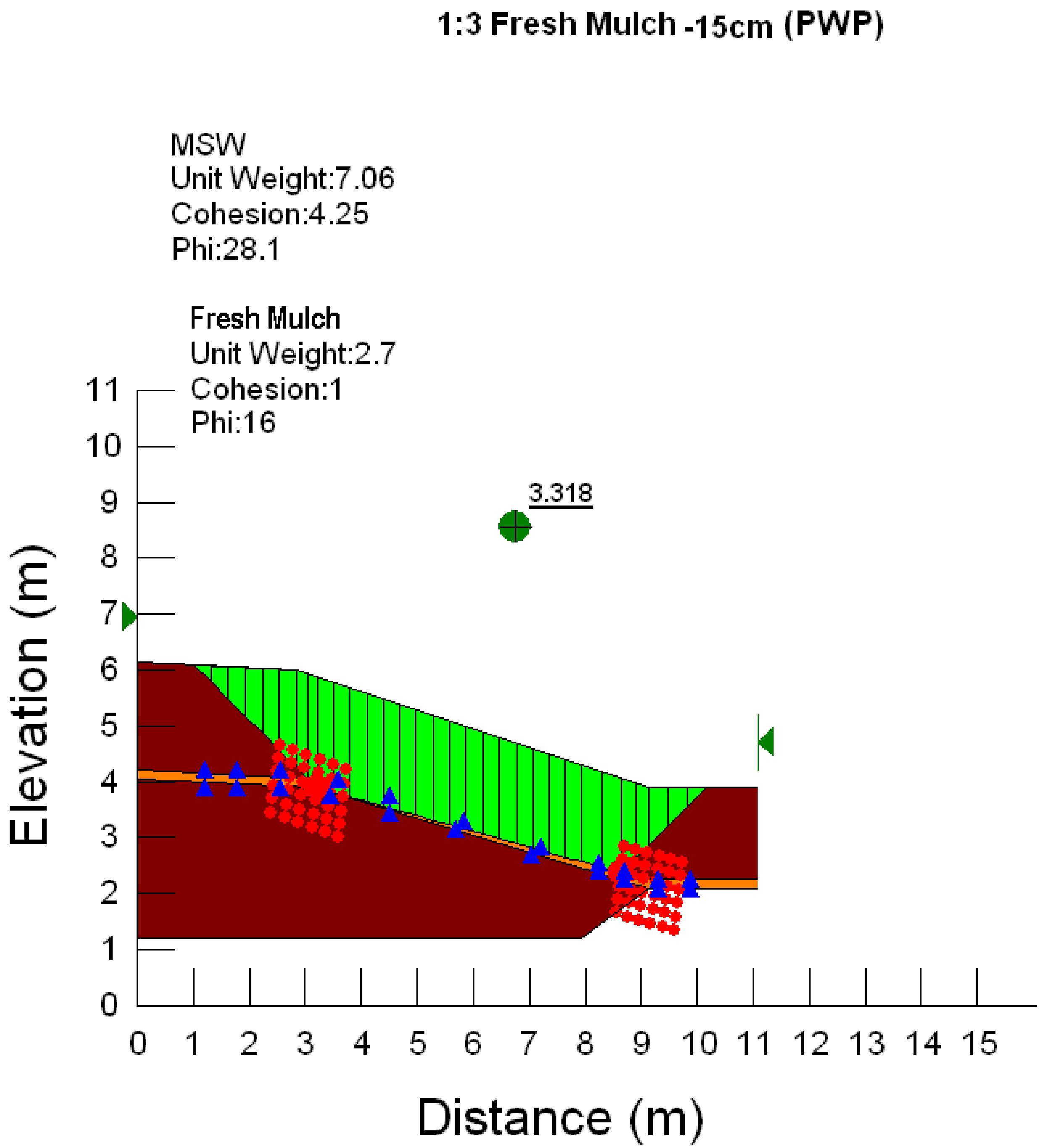
1:4 Fresh Mix-45cm
MSW
Unit Weight:7.06
Cohesion:4.25
Phi:28.1
Fresh Mix
Unit Weight: 5.6
Cohesion:1
Phi:15
3.505
Elevation (m)
Distance (m)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

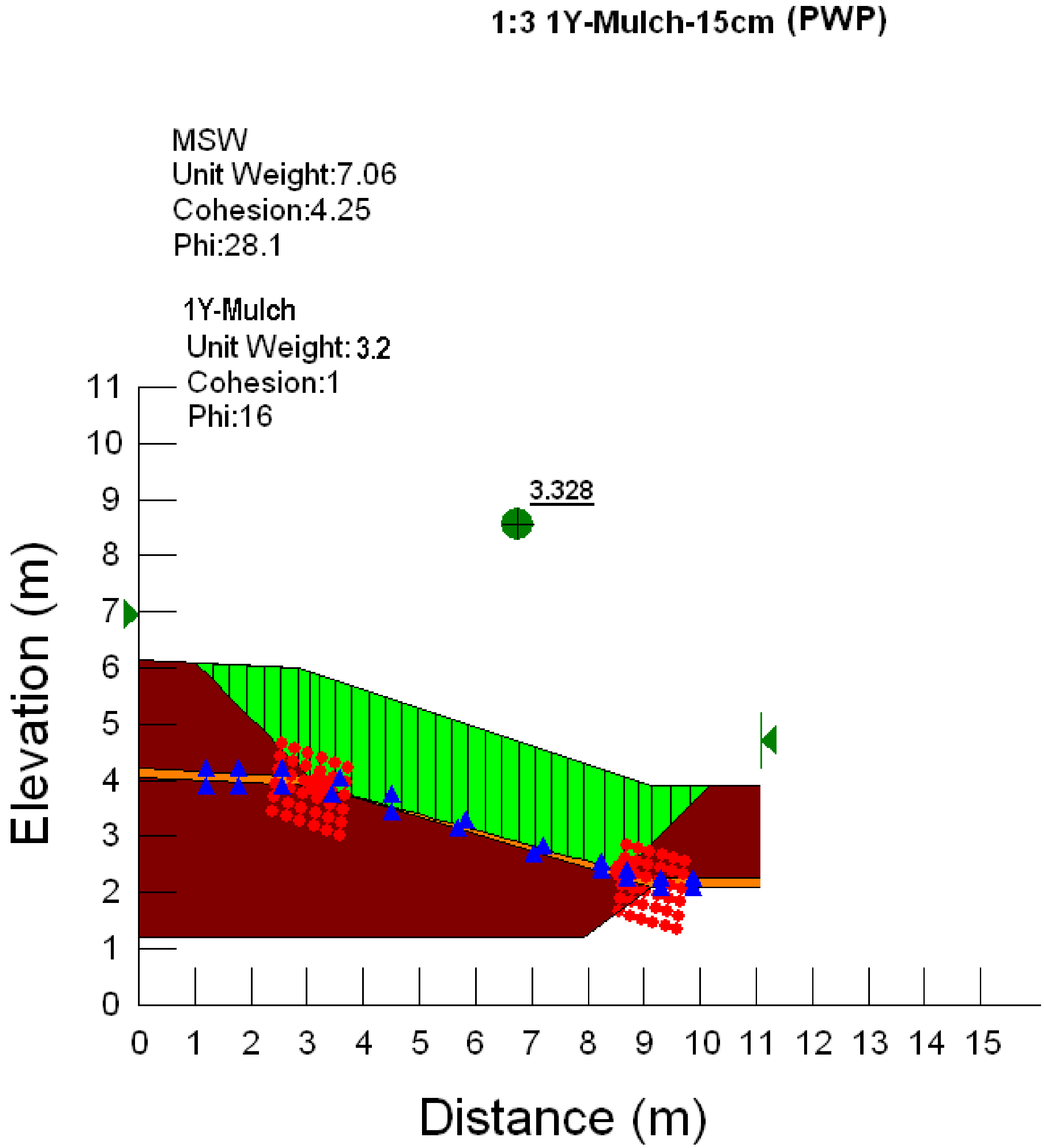

1:4 1Y-Mix-45cm
MSW
Unit Weight:7.06
Cohesion:4.25
Phi:28.1
1Y-Mix
Unit Weight: 6.7
Cohesion: 0
Phi: 12
2.872
Elevation (m)
Distance (m)
0 1 2 3 4 5 6 7 8 9 10 11
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15

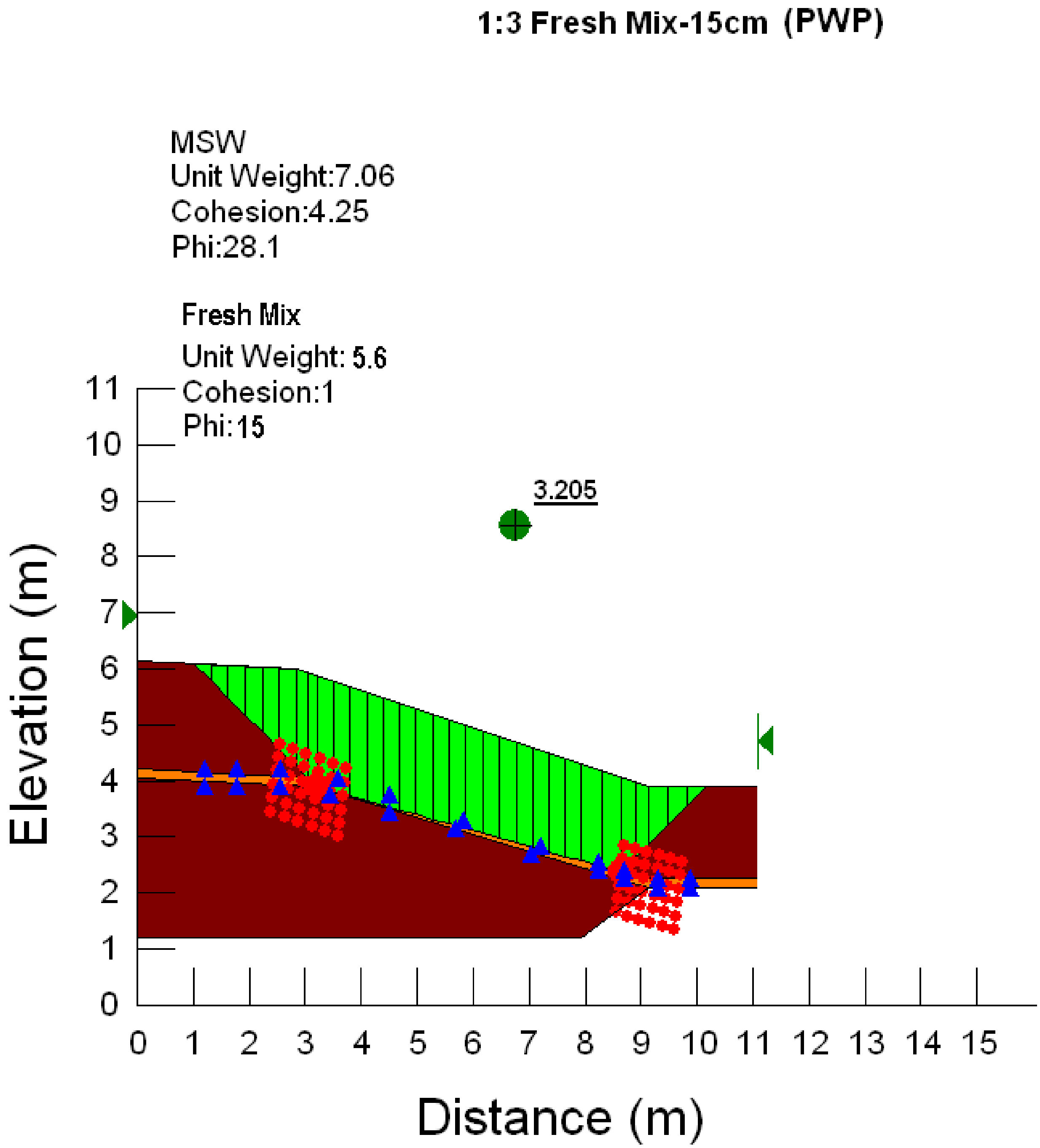

1:4 3Y-Mix-45cm
MSW
Unit Weight:7.06
Cohesion:4.25
Phi:28.1
3Y-Mix
Unit Weight: 9.4
Cohesion:0
Phi:11
2.708
Elevation (m)
Distance (m)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

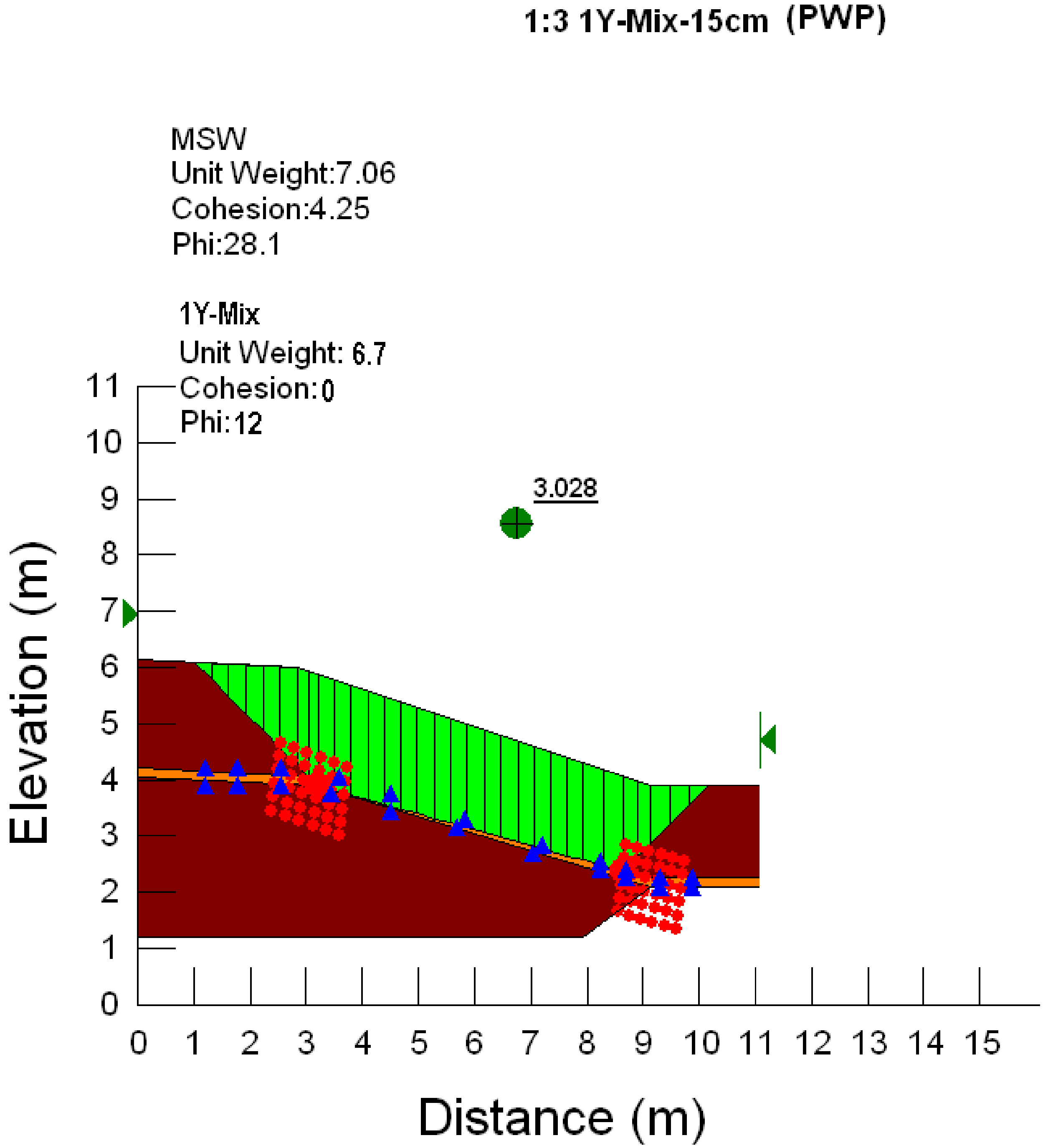

1:4 Soil -45cm
MSW
Unit Weight:7.06
Cohesion:4.25
Phi:28.1
Soil
Unit Weight: 12
Cohesion: 0
Phi: 10
2.455
Elevation (m)
Distance (m)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

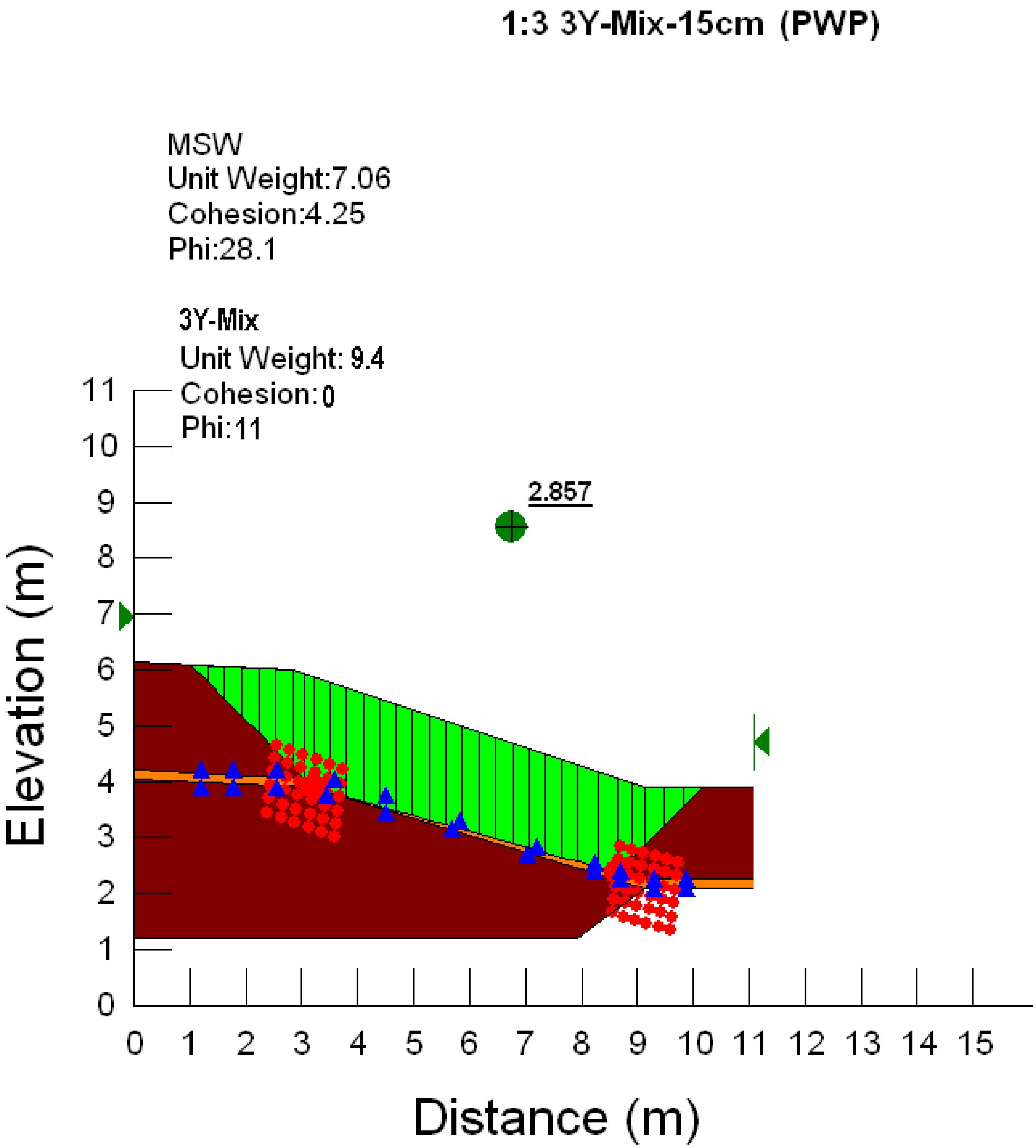
Block Failure/PWP (Slope 1:3 / Cover Depth = 15cm)

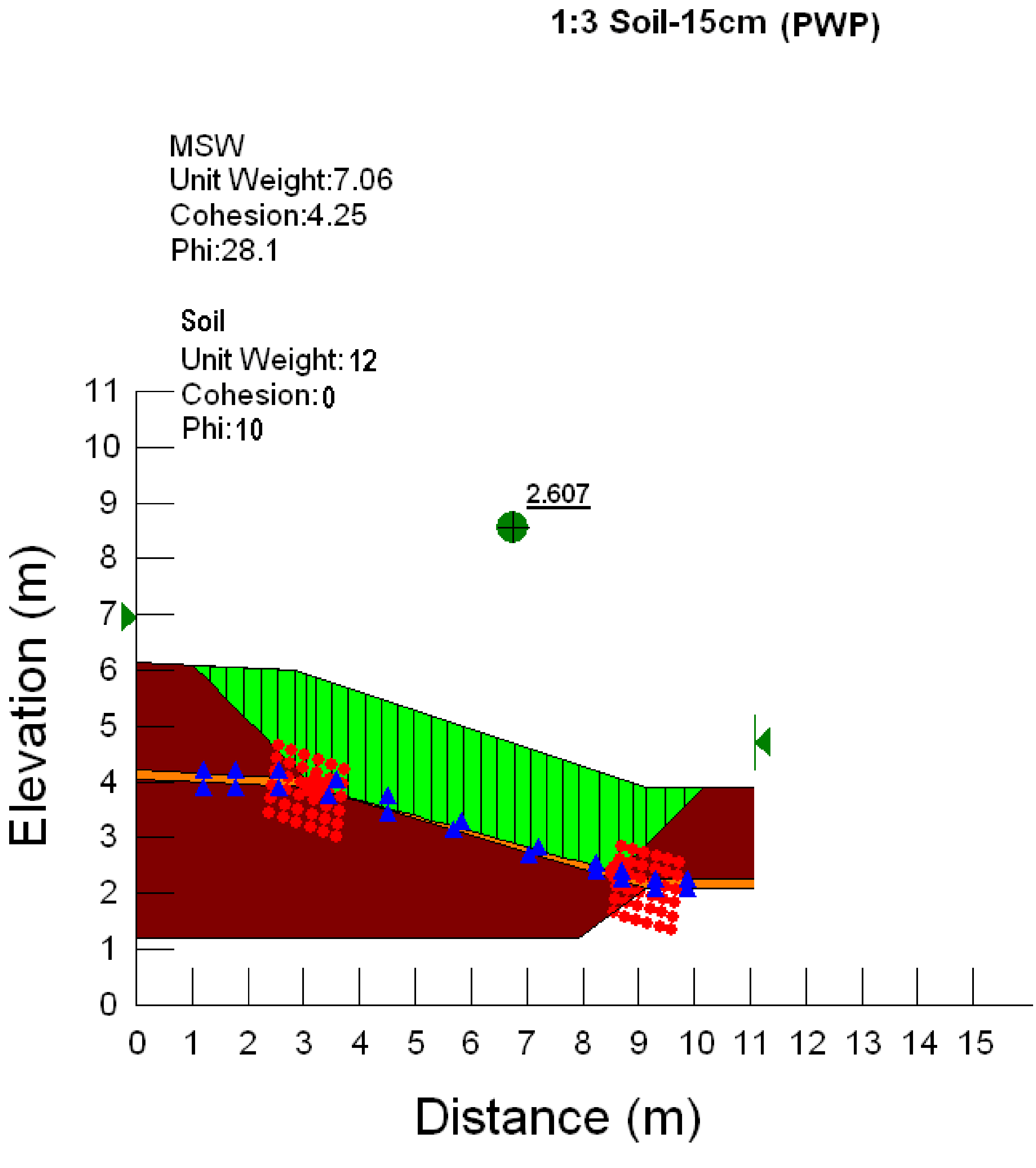



1:3 1Y-Mulch-15cm (PWP)
MSW
Unit Weight:7.06
Cohesion:4.25
Phi:28.1
1Y-Mulch
Unit Weight: 3.2
Cohesion:1
Phi:16
3.328
Elevation (m)
Distance (m)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15


1:3 Fresh Mix-15cm (PWP)
MSW
Unit Weight:7.06
Cohesion:4.25
Phi:28.1
Fresh Mix
Unit Weight: 5.6
Cohesion:1
Phi:15
3.205
Elevation (m)
Distance (m)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

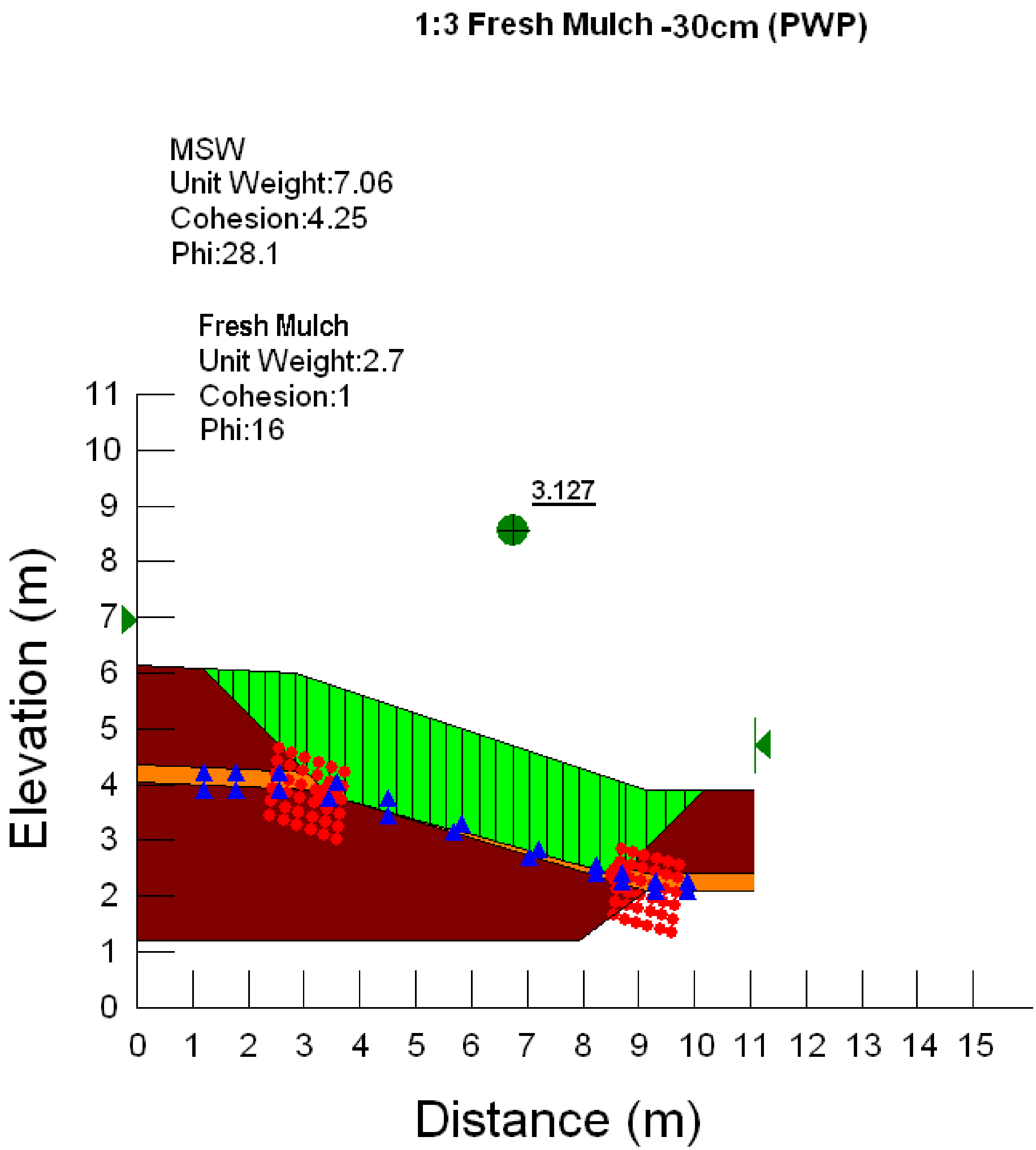

1:3 1Y-Mix-15cm (PWP)
MSW
Unit Weight:7.06
Cohesion:4.25
Phi:28.1
1Y-Mix
Unit Weight: 6.7
Cohesion:0
Phi:12
3.028
Elevation (m)
Distance (m)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

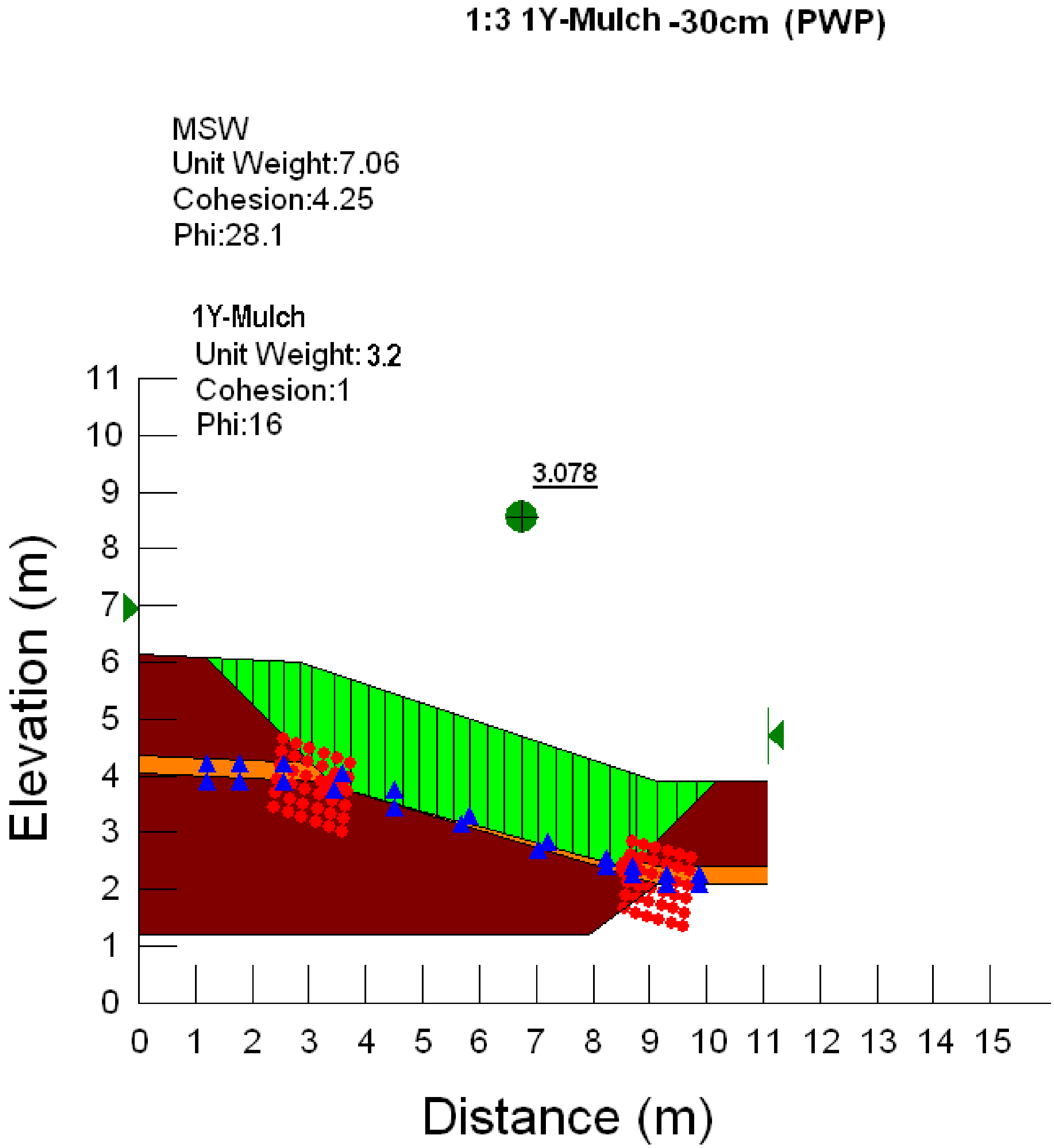

1:3 3Y-Mix-15cm (PWP)
MSW
Unit Weight:7.06
Cohesion:4.25
Phi:28.1
3Y-Mix
Unit Weight: 9.4
Cohesion: 0
Phi: 11
2.857
Elevation (m)
Distance (m)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15



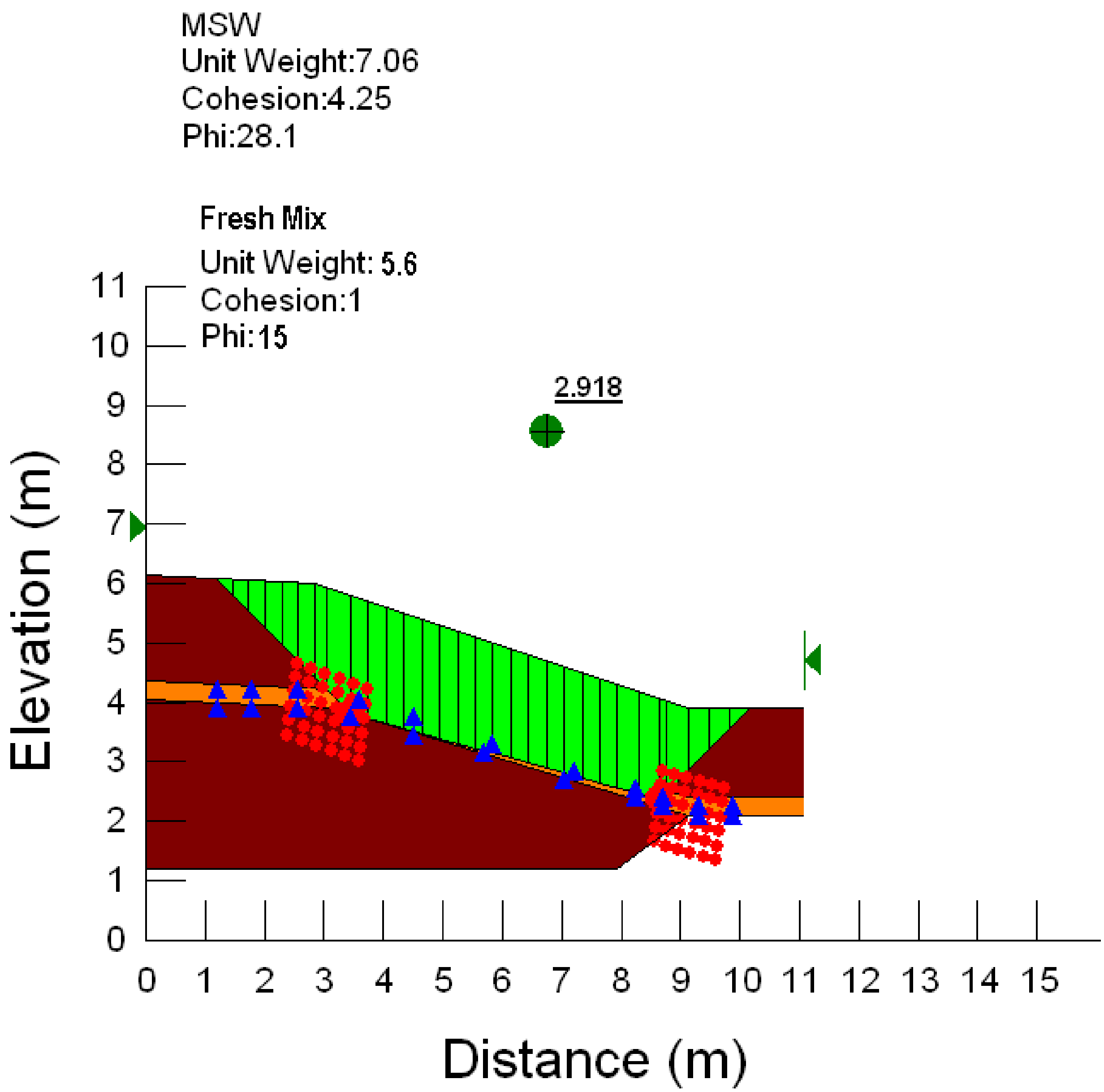
1:3 Soil-15cm (PWP)
MSW
Unit Weight:7.06
Cohesion:4.25
Phi:28.1
Soil
Unit Weight: 12
Cohesion: 0
Phi: 10
2.607
Elevation (m)
Distance (m)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

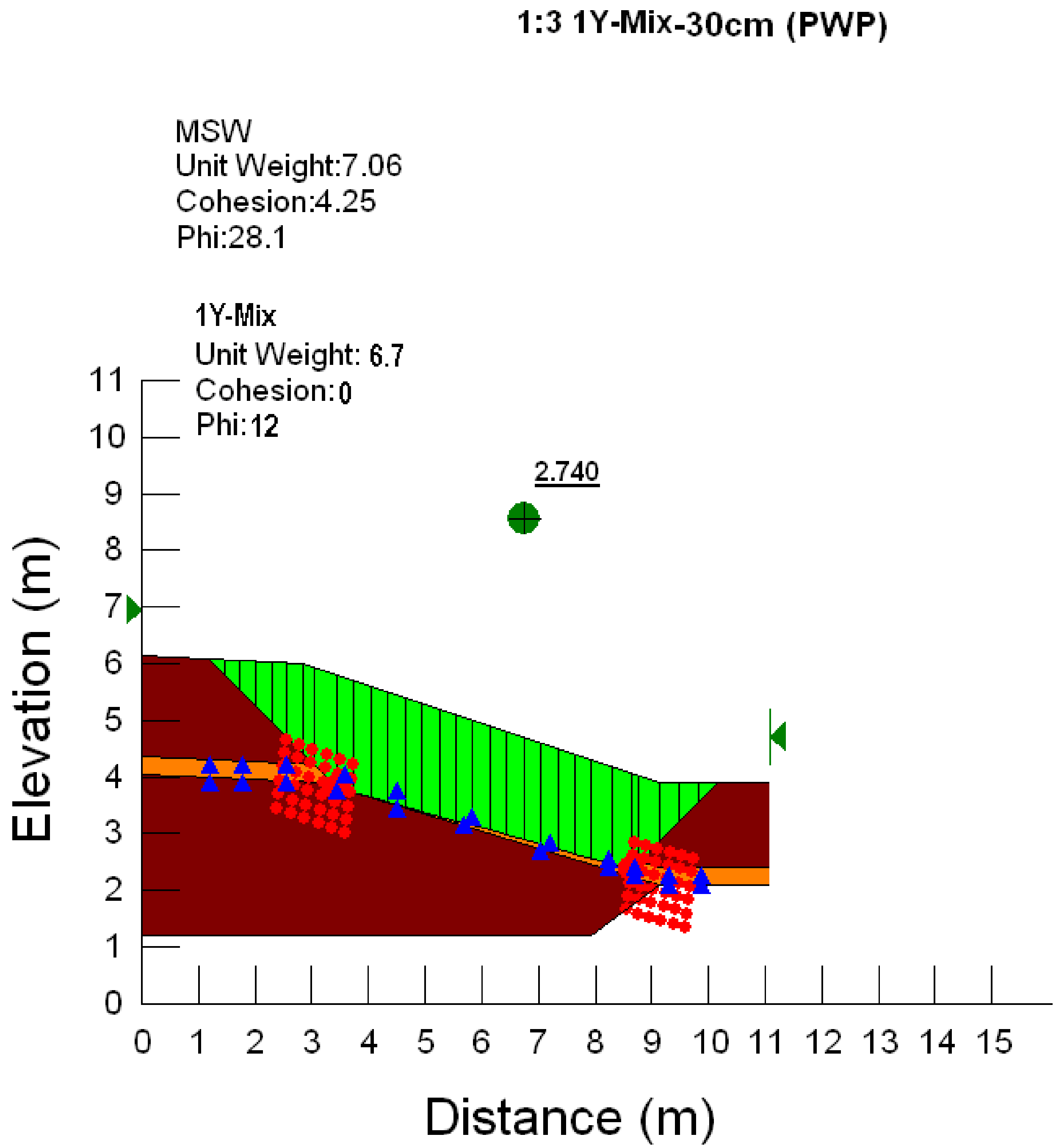
Block Failure/PWP (Slope 1:3 / Cover Depth = 30cm)

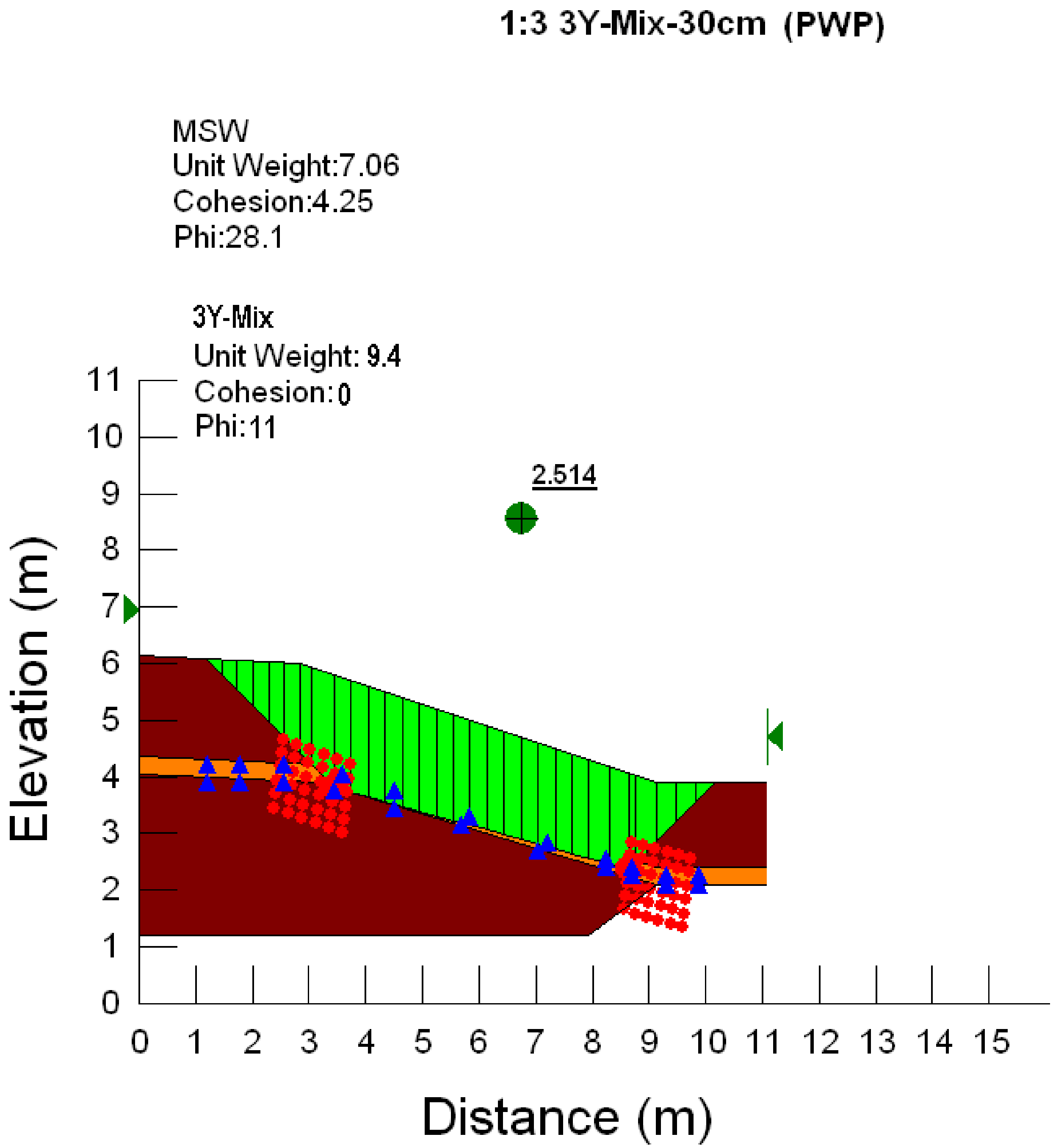


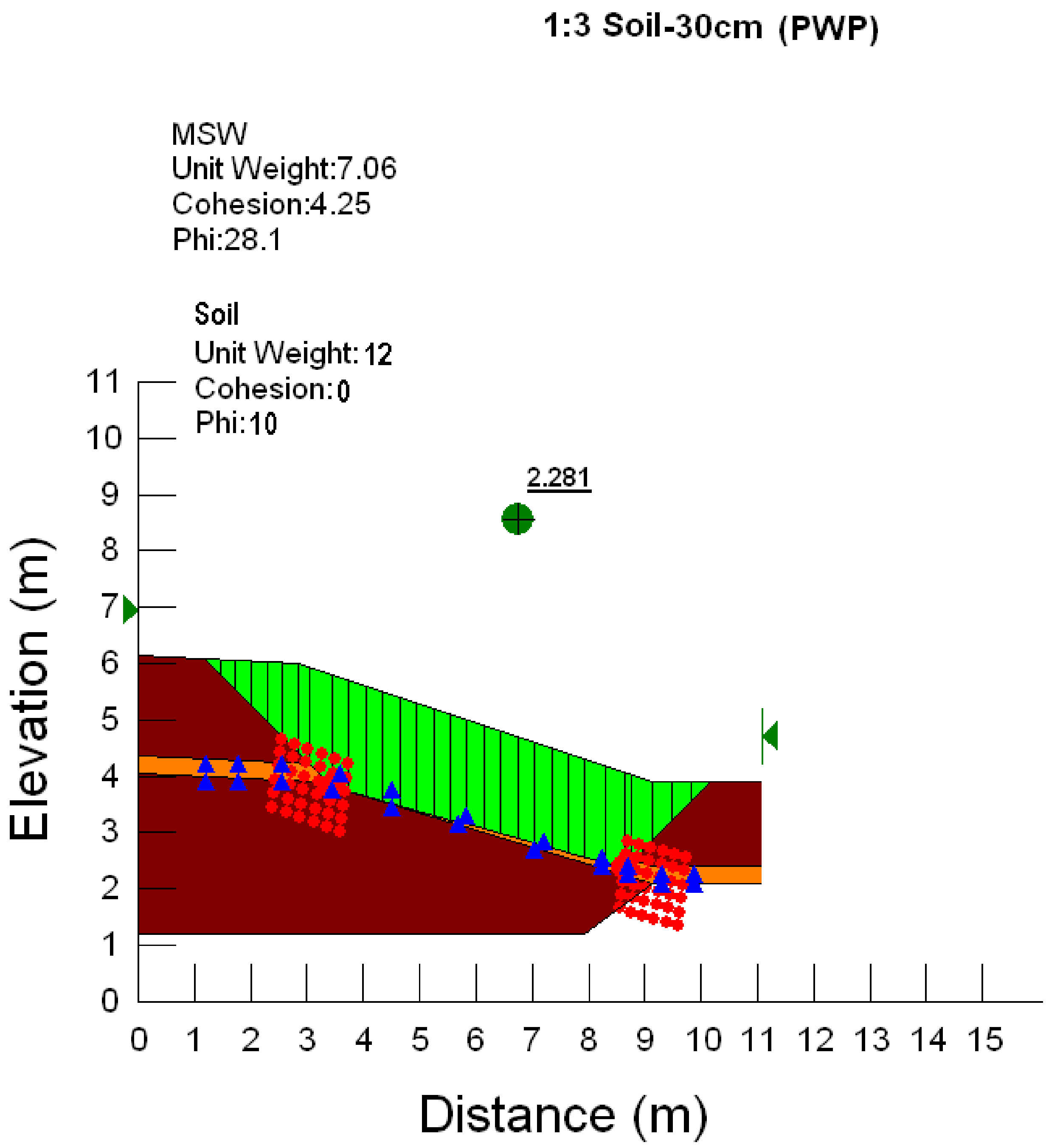

1:3 1Y-Mulch -30cm (PWP)
MSW
Unit Weight:7.06
Cohesion:4.25
Phi:28.1
1Y-Mulch
Unit Weight: 3.2
Cohesion:1
Phi:16
3.078
Elevation (m)
Distance (m)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

1:3 Fresh Mix-30cm (PWP)



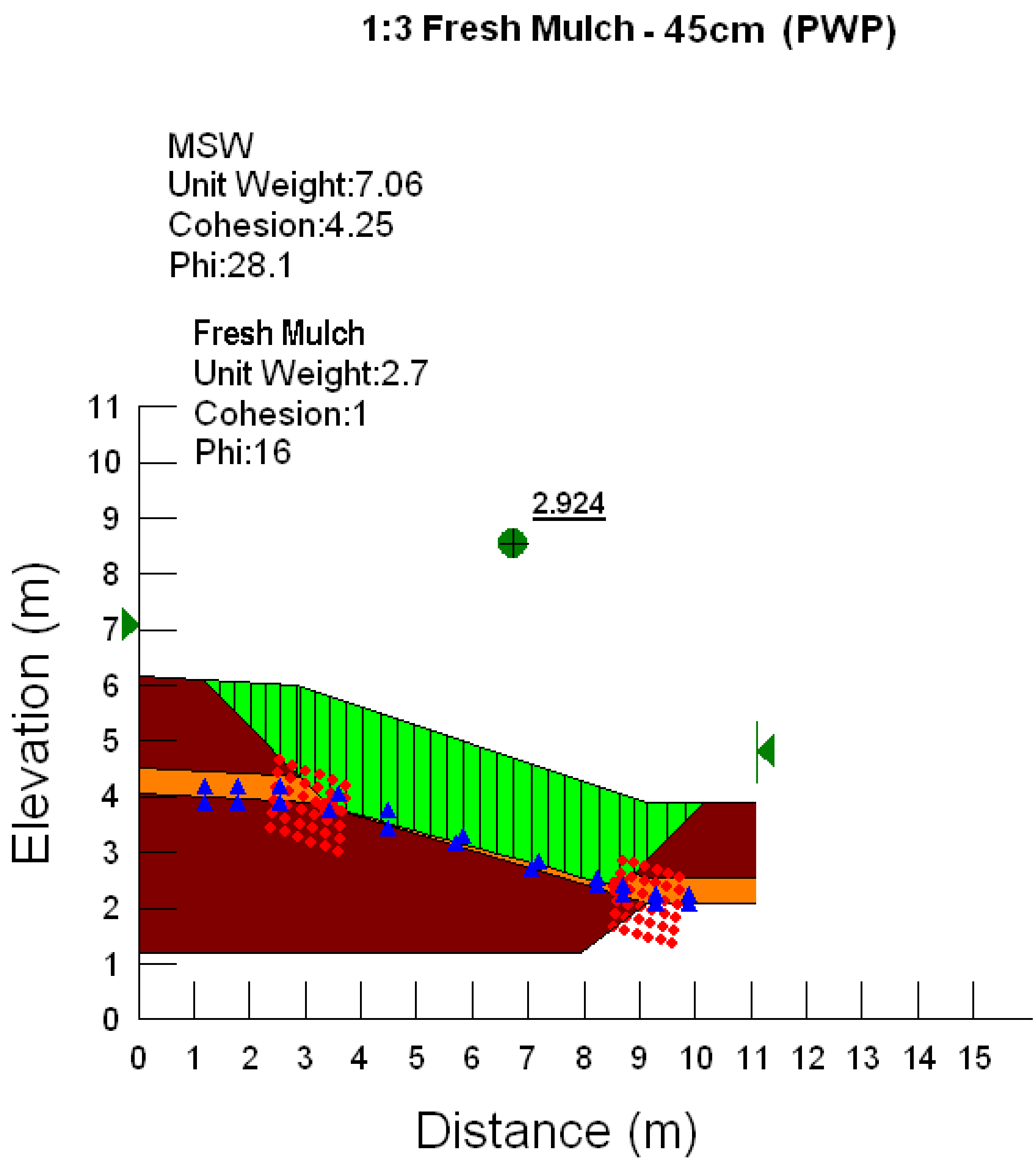

1:3 1Y-Mix-30cm (PWP)
MSW
Unit Weight:7.06
Cohesion:4.25
Phi:28.1
1Y-Mix
Unit Weight: 6.7
Cohesion:0
Phi:12
2.740
Elevation (m)
Distance (m)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15


1:3 3Y-Mix-30cm (PWP)
MSW
Unit Weight:7.06
Cohesion:4.25
Phi:28.1
3Y-Mix
Unit Weight: 9.4
Cohesion: 0
Phi: 11
2.514
Elevation (m)
Distance (m)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

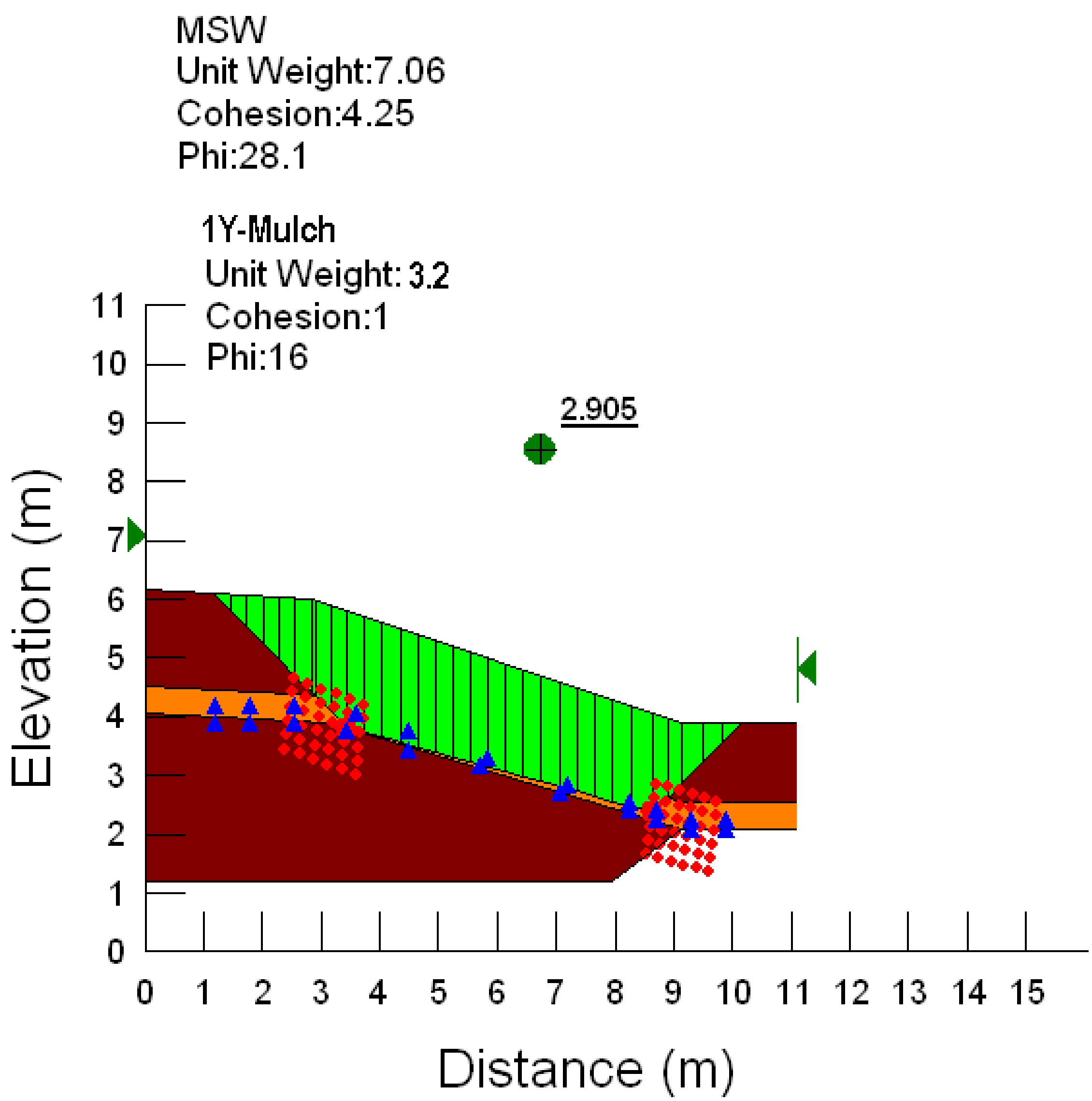


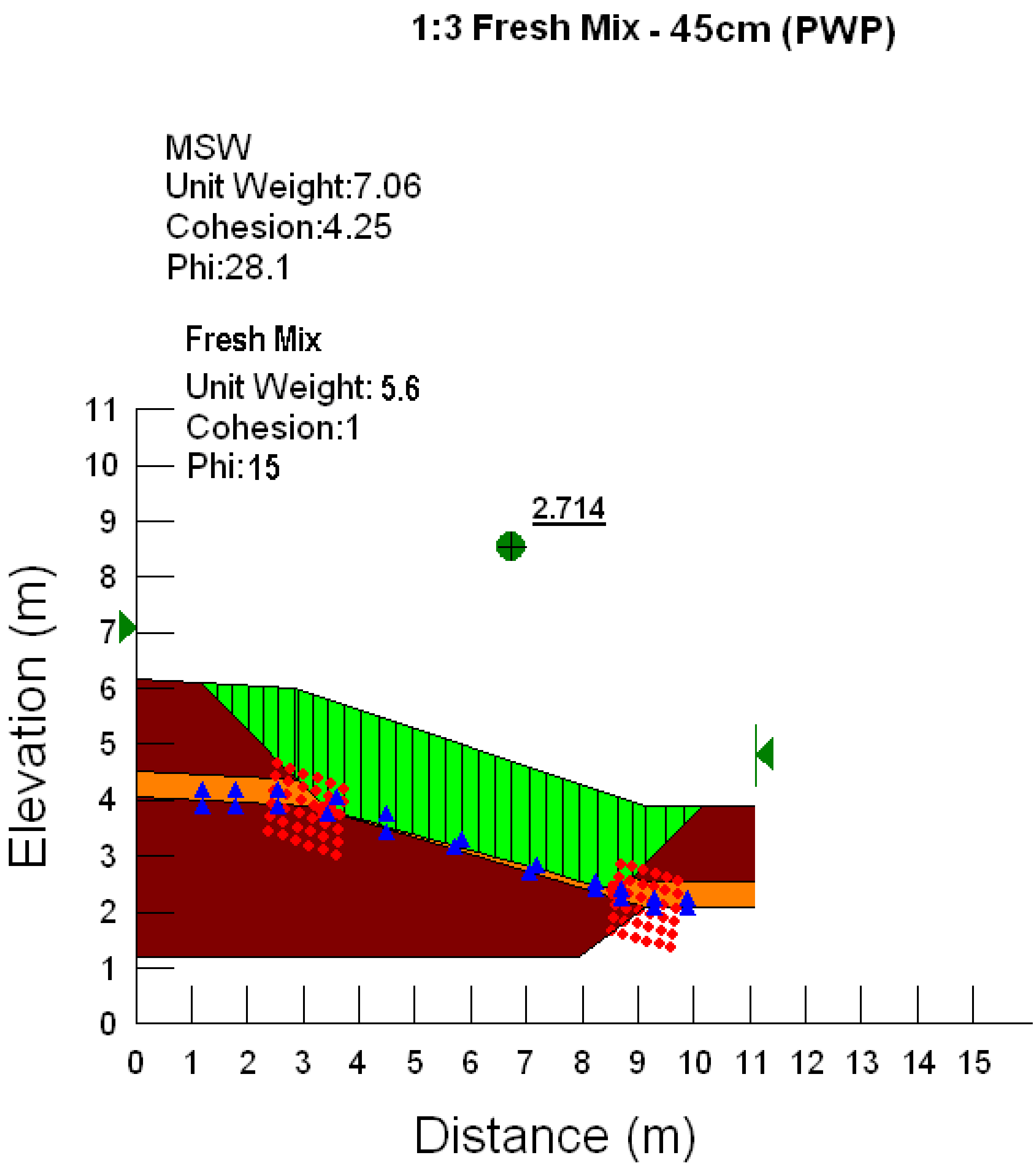
1:3 Soil-30cm (PWP)
MSW
Unit Weight:7.06
Cohesion:4.25
Phi:28.1
Soil
Unit Weight: 12
Cohesion: 0
Phi: 10
2.281
Elevation (m)
Distance (m)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

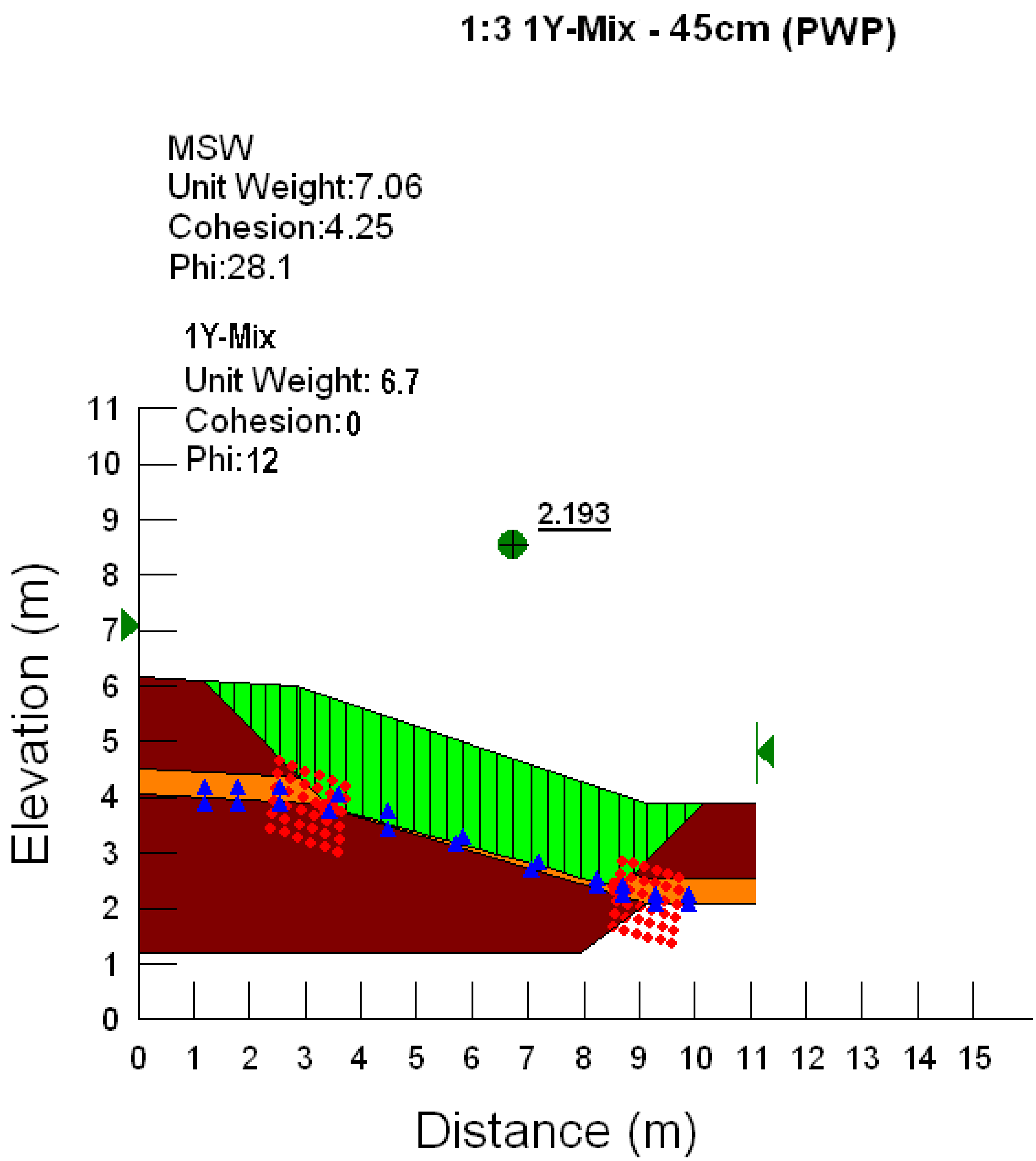
Block Failure/PWP (Slope 1:3 / Cover Depth = 45cm)

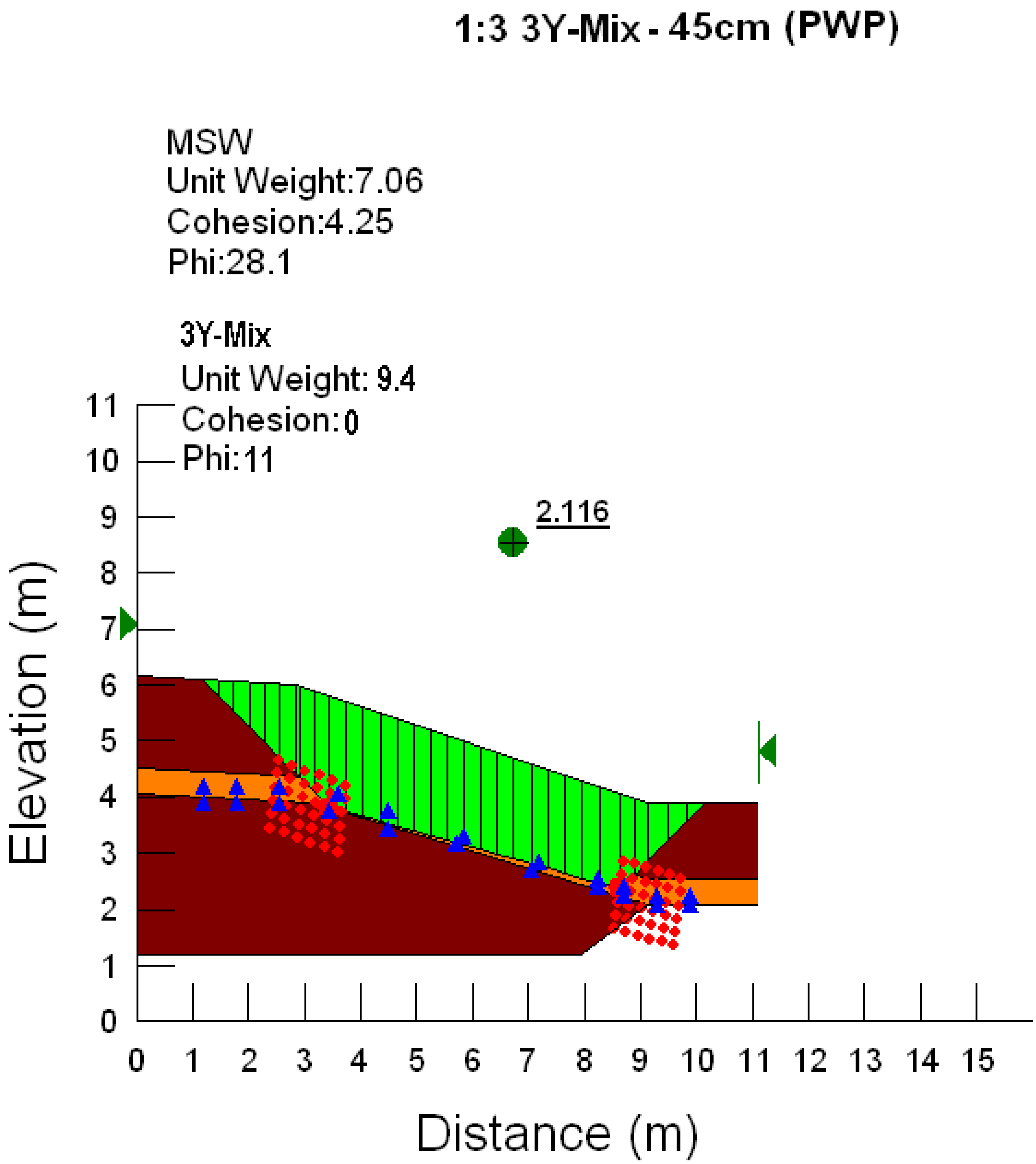


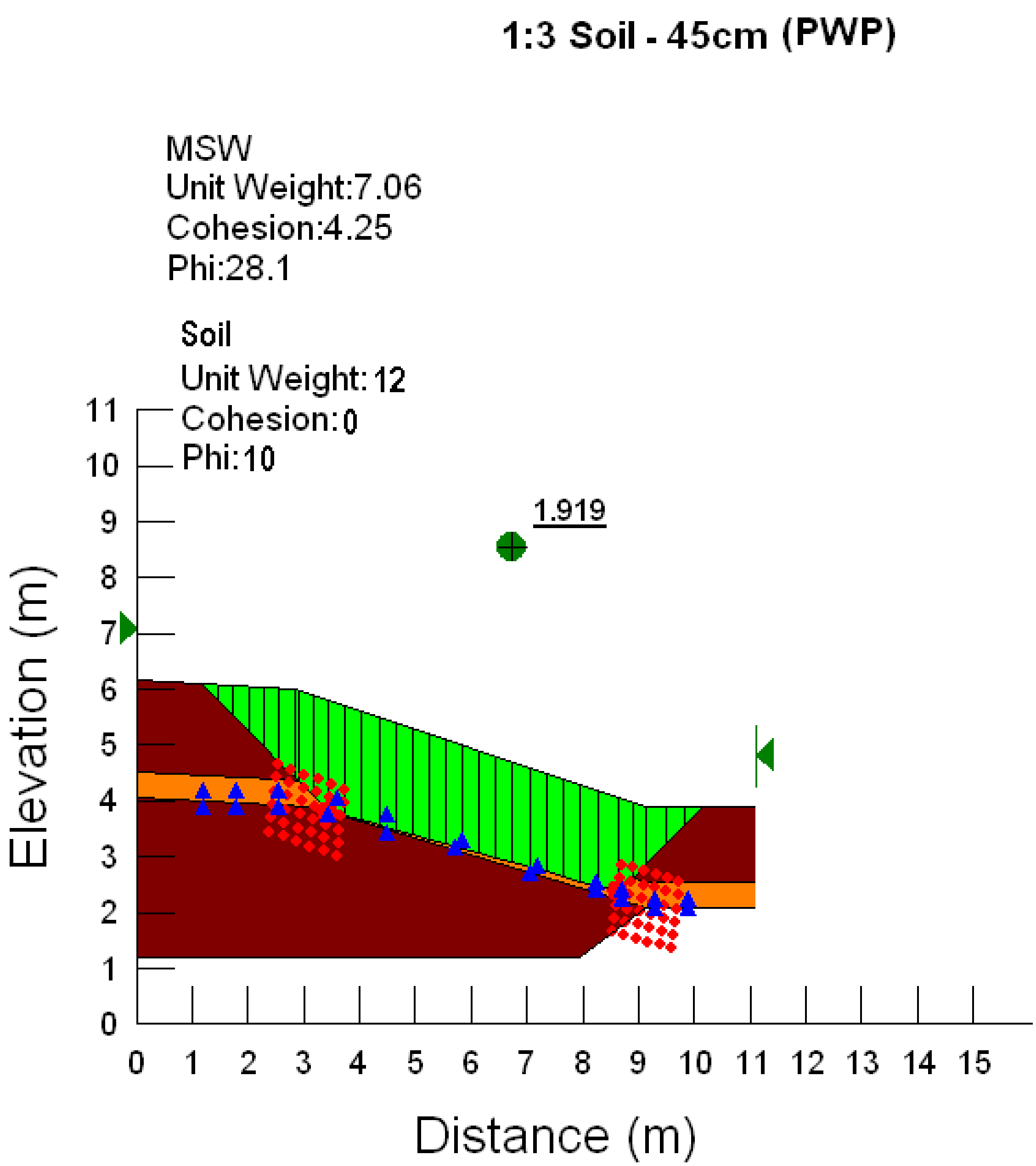
1:3 1Y-Mulch - 45cm (PWP)



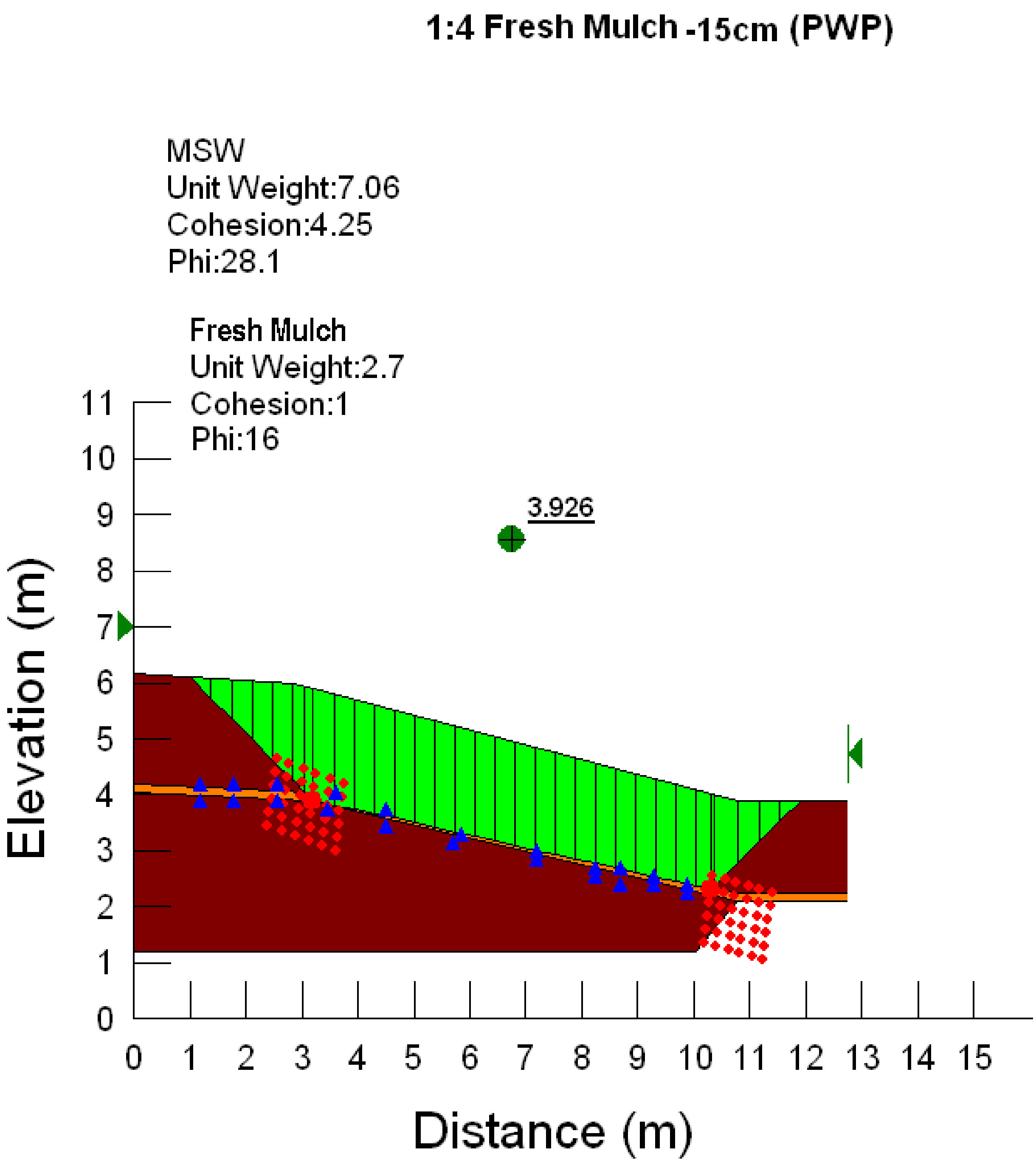

1:3 Fresh Mix - 45cm (PWP)
MSW
Unit Weight:7.06
Cohesion:4.25
Phi:28.1
Fresh Mix
Unit Weight: 5.6
Cohesion:1
Phi:15
2.714
Elevation (m)
Distance (m)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

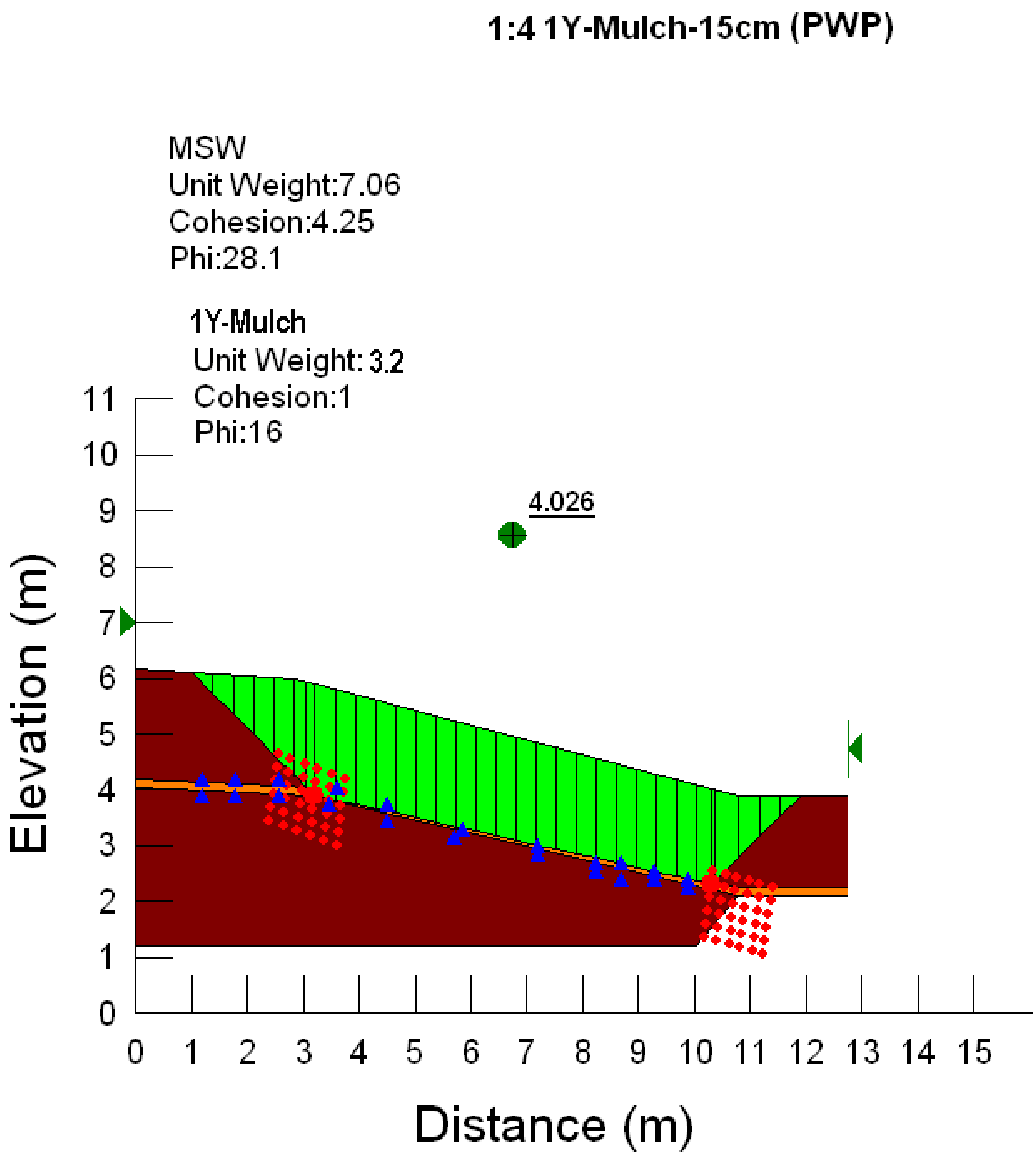

1:3 1Y-Mix - 45cm (PWP)
MSW
Unit Weight:7.06
Cohesion:4.25
Phi:28.1
1Y-Mix
Unit Weight: 6.7
Cohesion: 0
Phi: 12
2.193
Elevation (m)
Distance (m)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15


1:3 3Y-Mix - 45cm (PWP)
MSW
Unit Weight:7.06
Cohesion:4.25
Phi:28.1
3Y-Mix
Unit Weight: 9.4
Cohesion: 0
Phi: 11
2.116
Elevation (m)
Distance (m)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

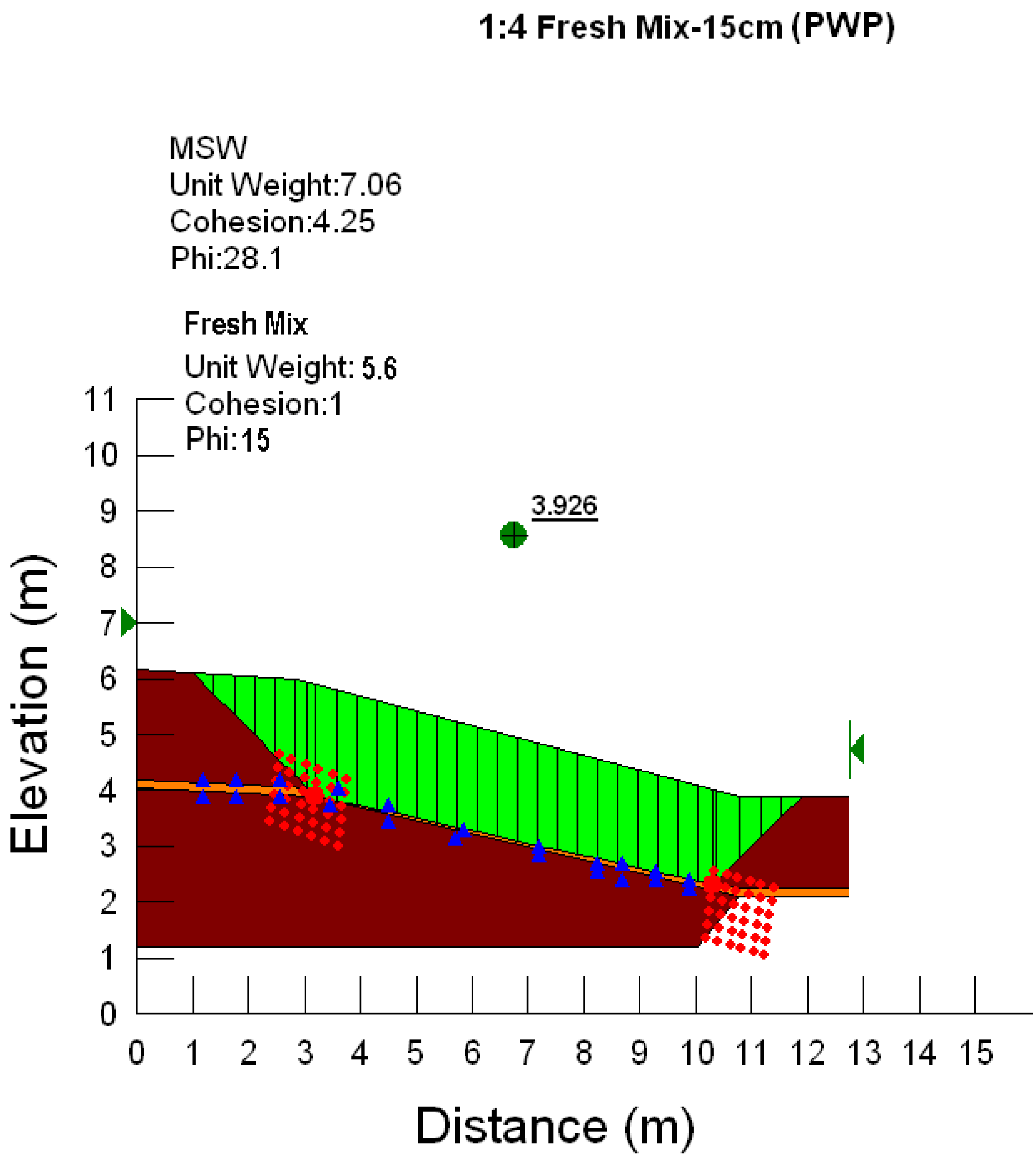

1:3 Soil - 45cm (PWP)
MSW
Unit Weight:7.06
Cohesion:4.25
Phi:28.1
Soil
Unit Weight: 12
Cohesion: 0
Phi: 10
1.919
Elevation (m)
Distance (m)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

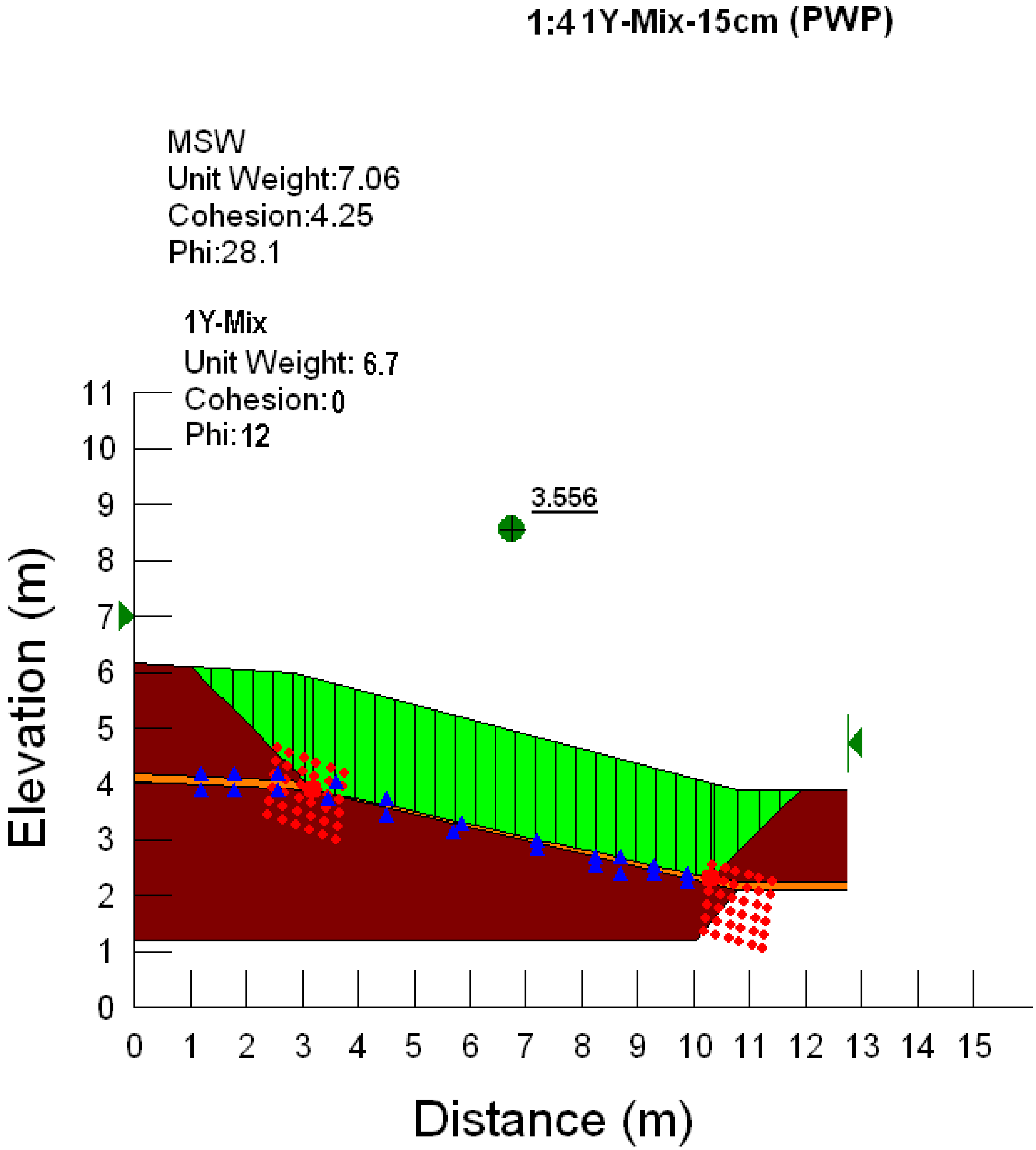
Block Failure/PWP (Slope 1:4 / Cover Depth = 15cm)



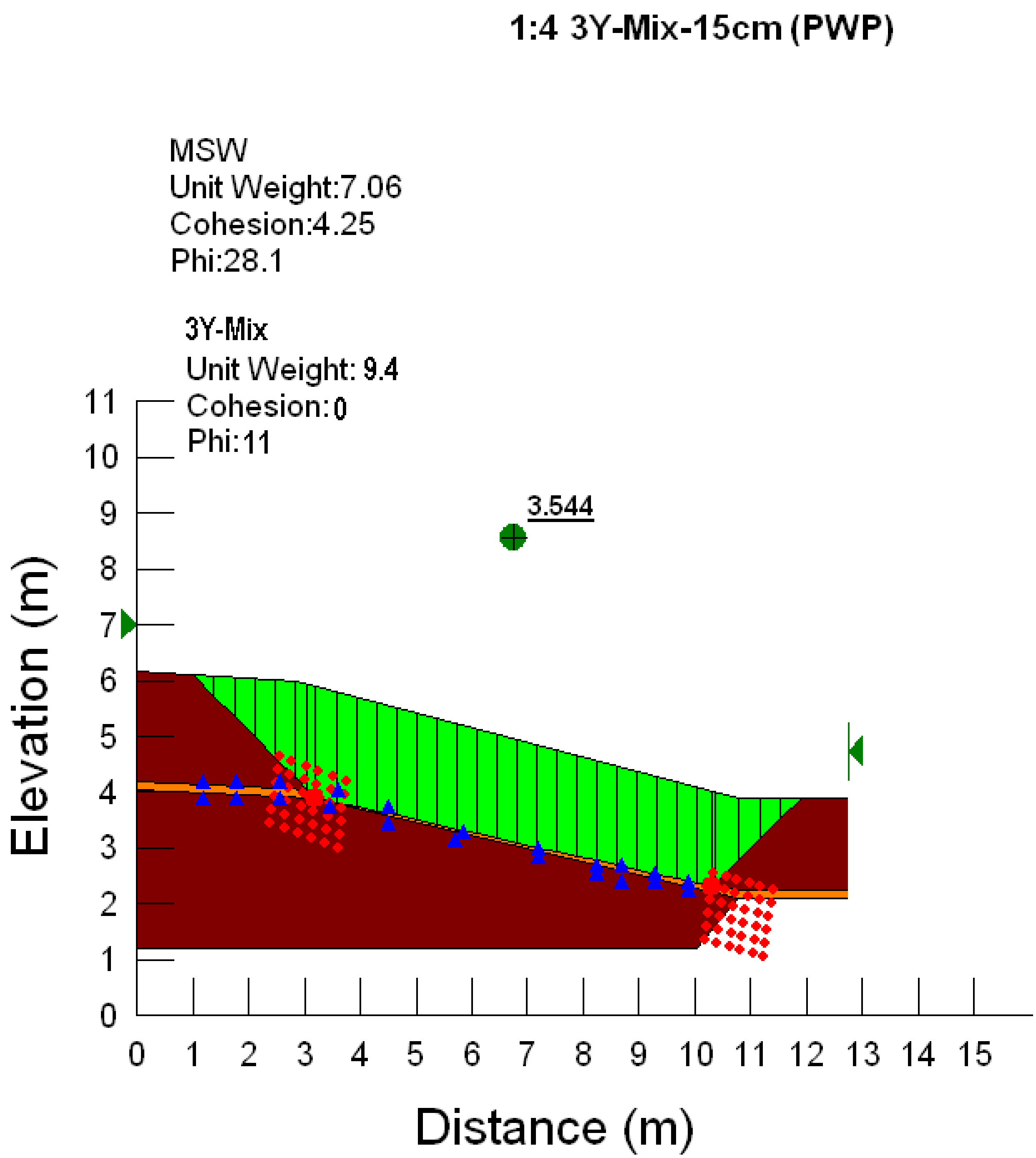


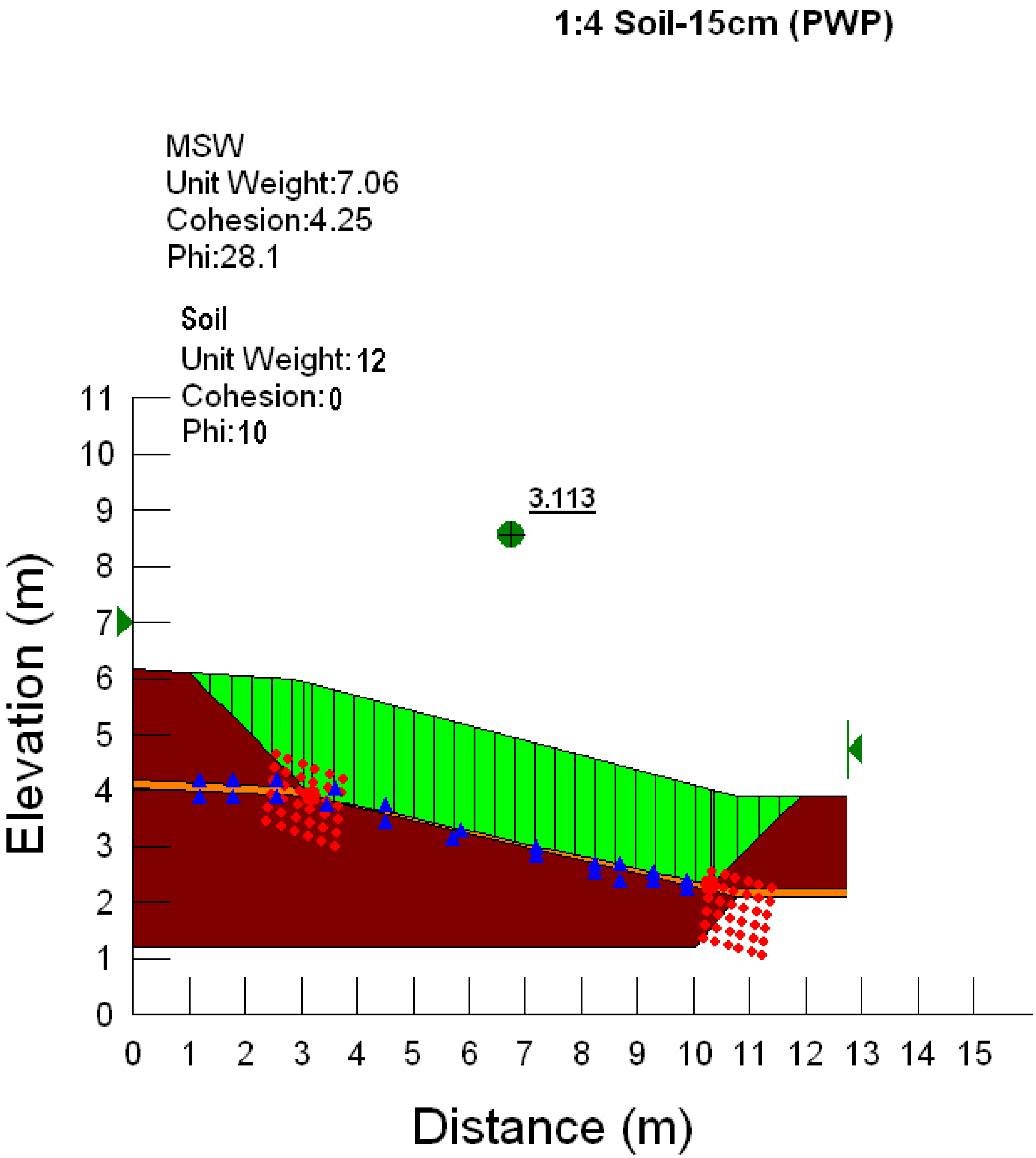
1:4 1Y-Mulch-15cm (PWP)
MSW
Unit Weight:7.06
Cohesion:4.25
Phi:28.1
1Y-Mulch
Unit Weight: 3.2
Cohesion:1
Phi:16
4.026
Elevation (m)
Distance (m)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15


1:4 Fresh Mix-15cm (PWP)
MSW
Unit Weight:7.06
Cohesion:4.25
Phi:28.1
Fresh Mix
Unit Weight: 5.6
Cohesion:1
Phi:15
3.926
Elevation (m)
Distance (m)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

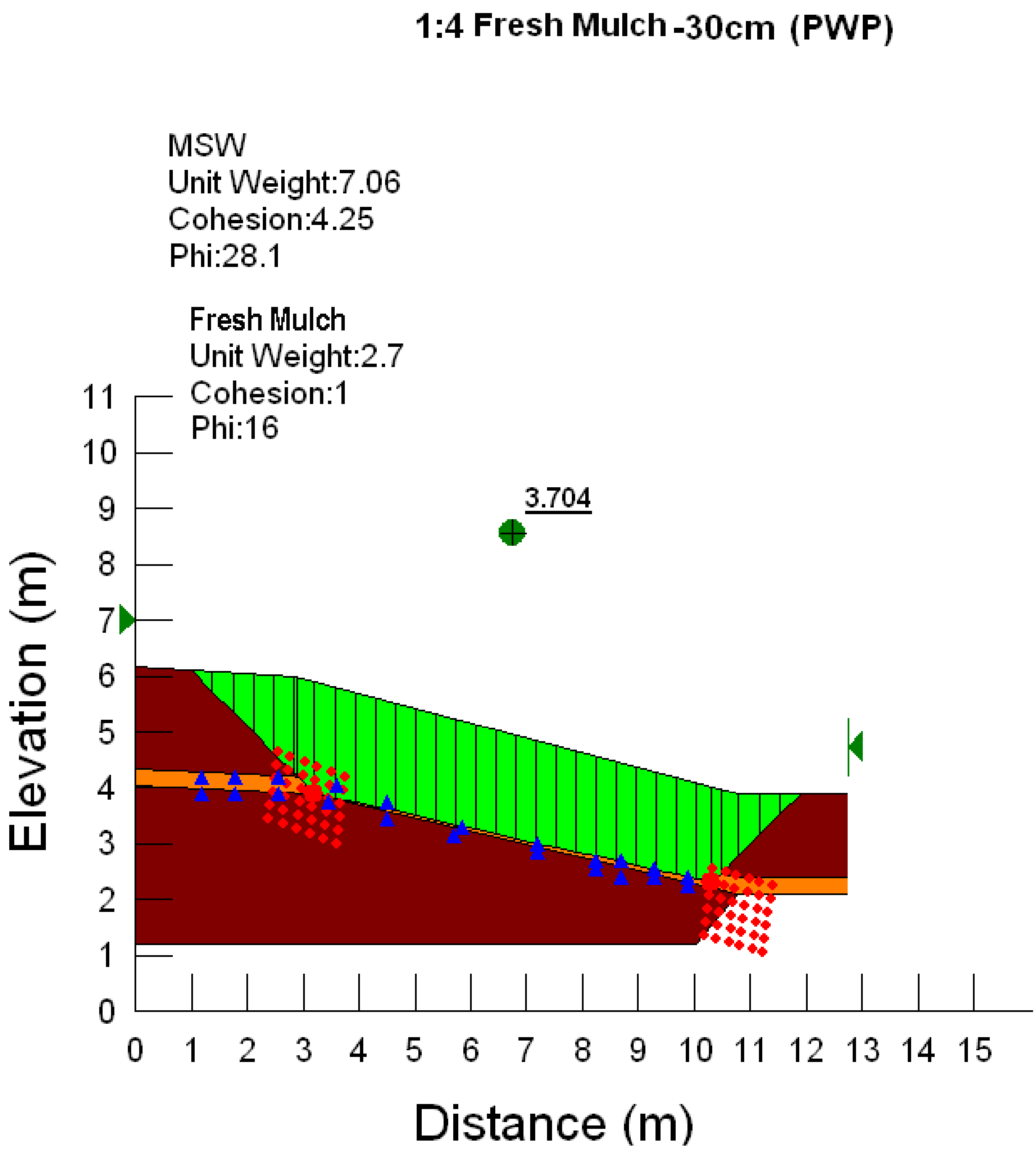


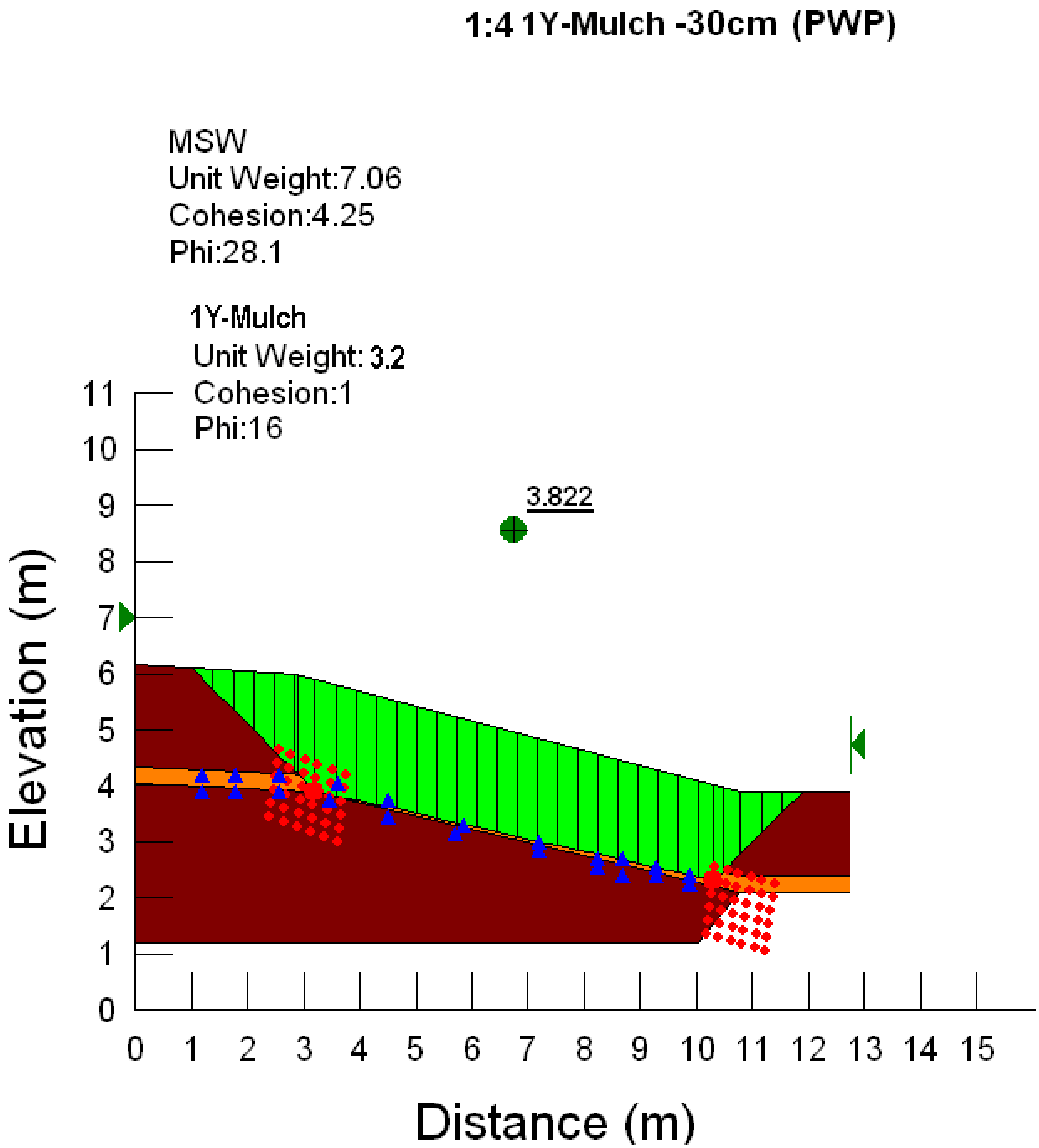
1:4 1Y-Mix-15cm (PWP)
MSW
Unit Weight:7.06
Cohesion:4.25
Phi:28.1
1Y-Mix
Unit Weight: 6.7
Cohesion: 0
Phi: 12
3.556
Elevation (m)
Distance (m)

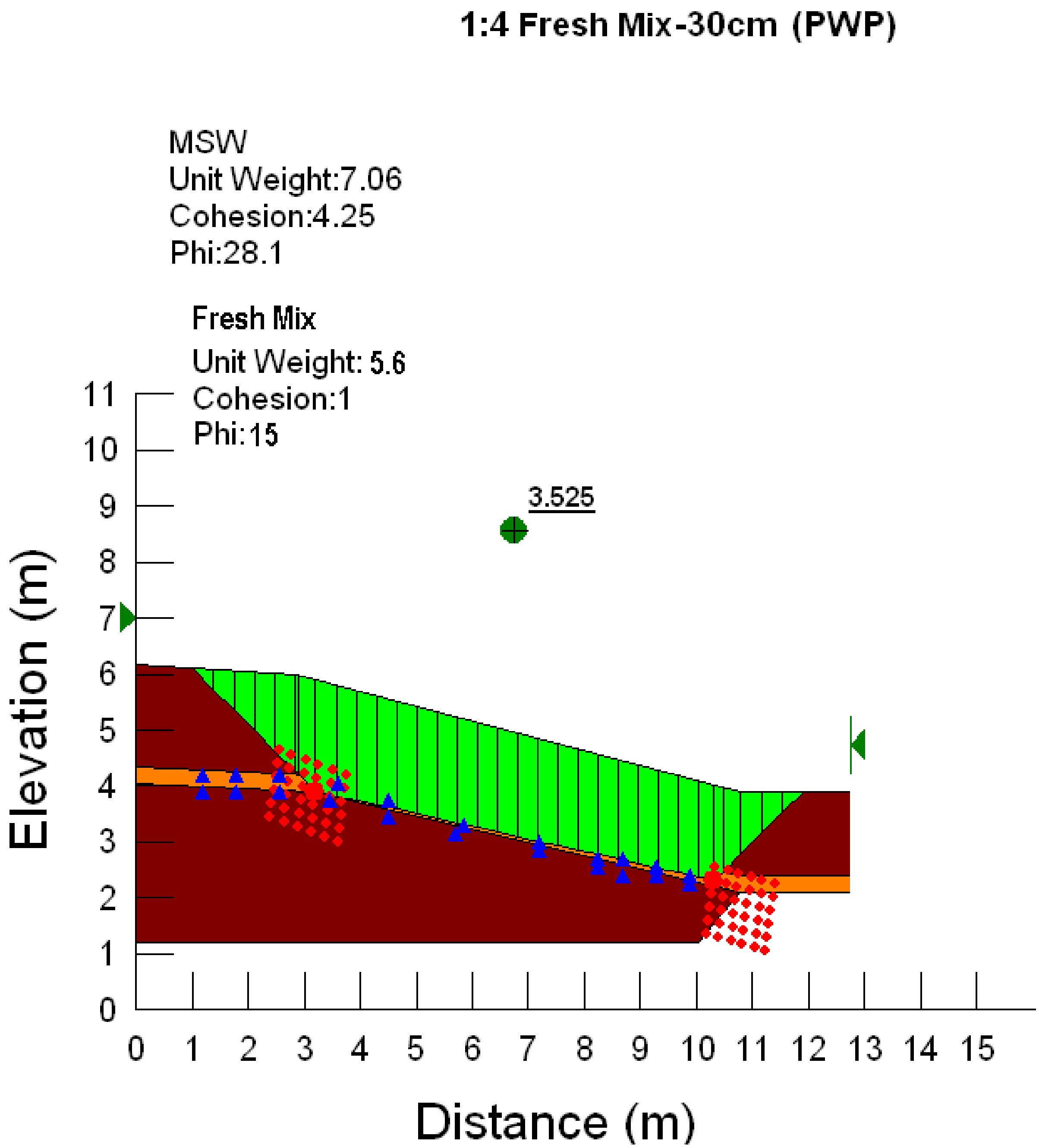

1:4 3Y-Mix-15cm (PWP)
MSW
Unit Weight:7.06
Cohesion:4.25
Phi:28.1
3Y-Mix
Unit Weight: 9.4
Cohesion: 0
Phi: 11
3.544
Elevation (m)
Distance (m)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15


1:4 Soil-15cm (PWP)
MSW
Unit Weight:7.06
Cohesion:4.25
Phi:28.1
Soil
Unit Weight: 12
Cohesion: 0
Phi: 10
3.113
Elevation (m)
Distance (m)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

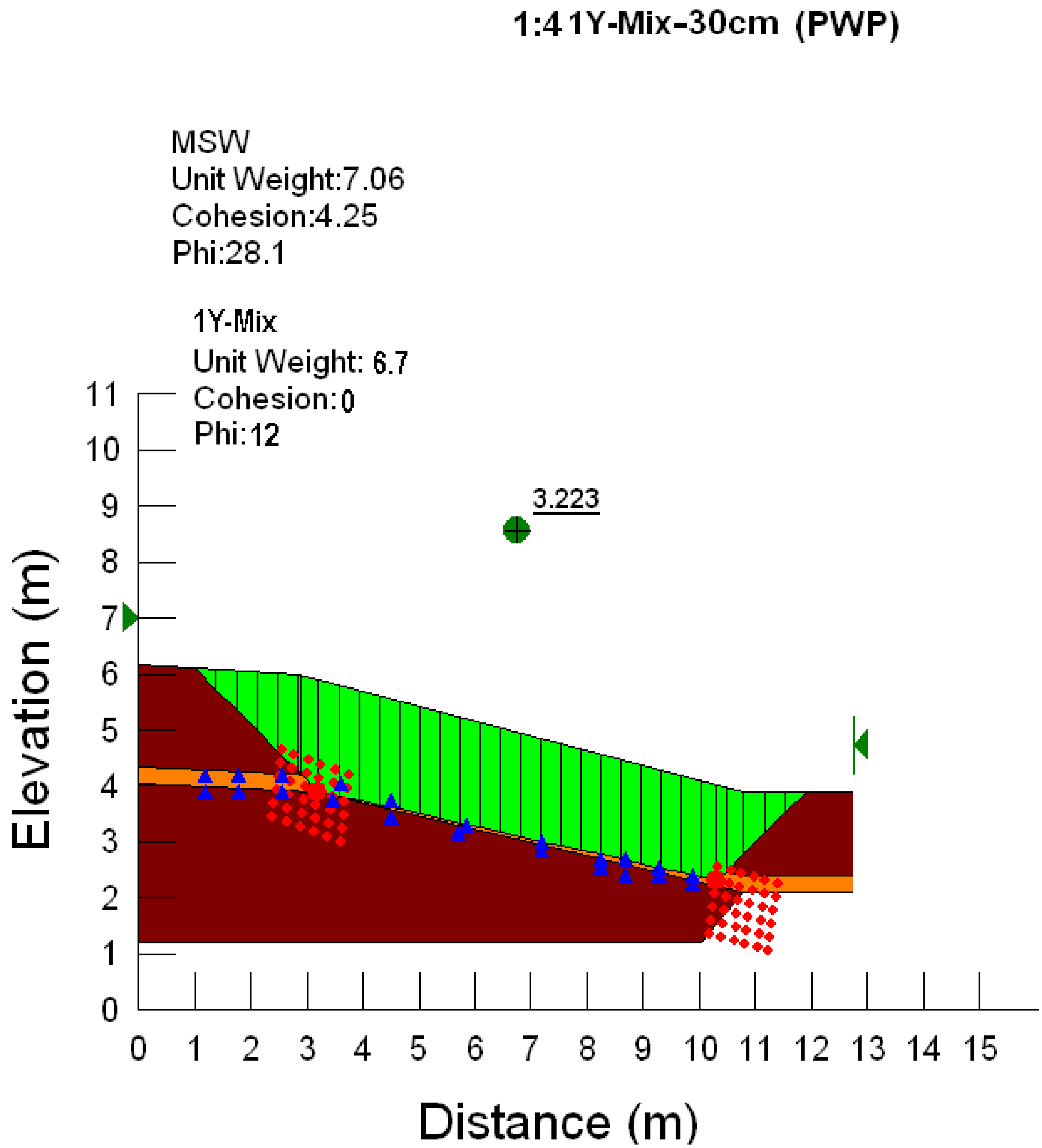
Block Failure/PWP (Slope 1:4 / Cover Depth = 30cm)

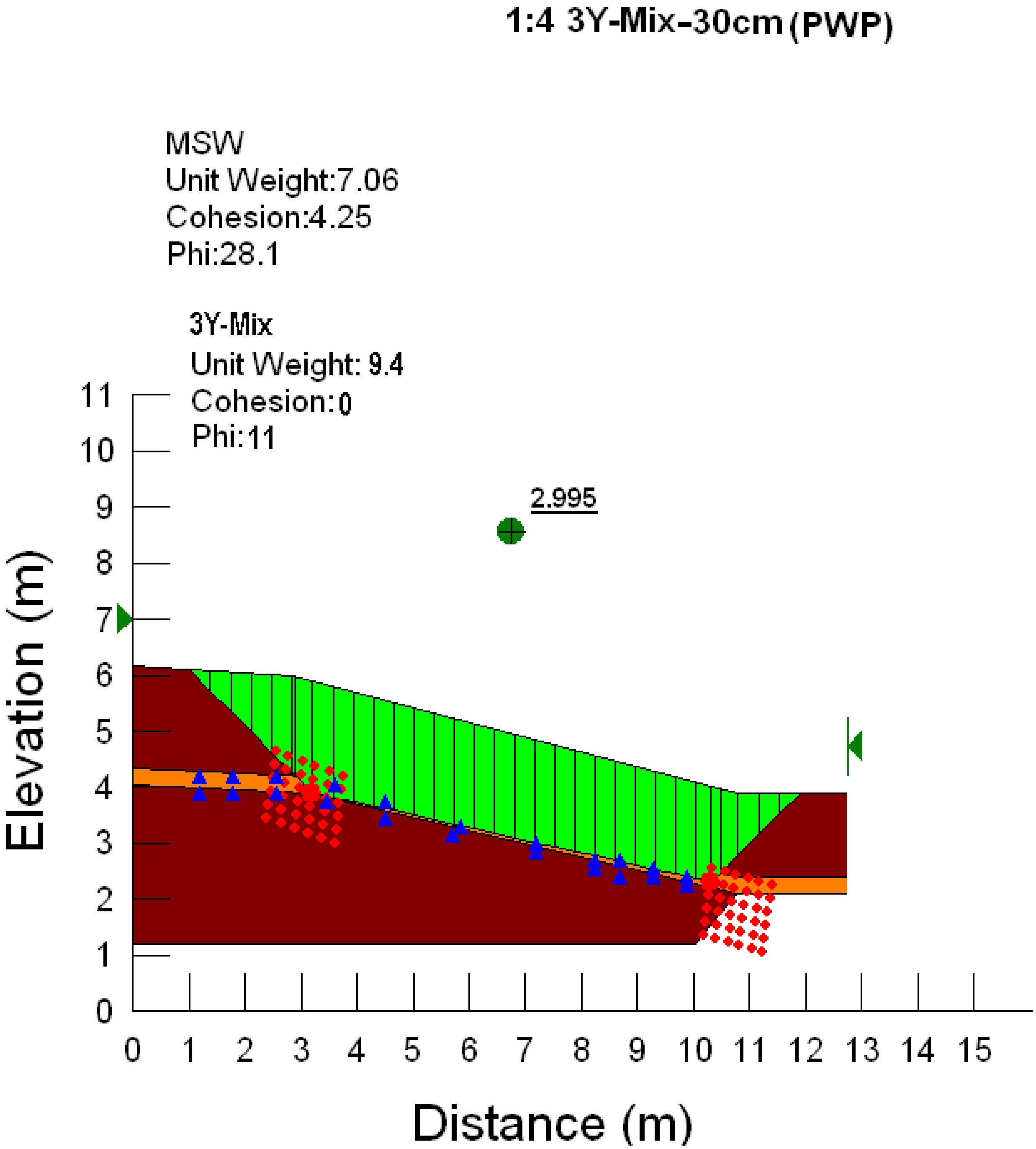


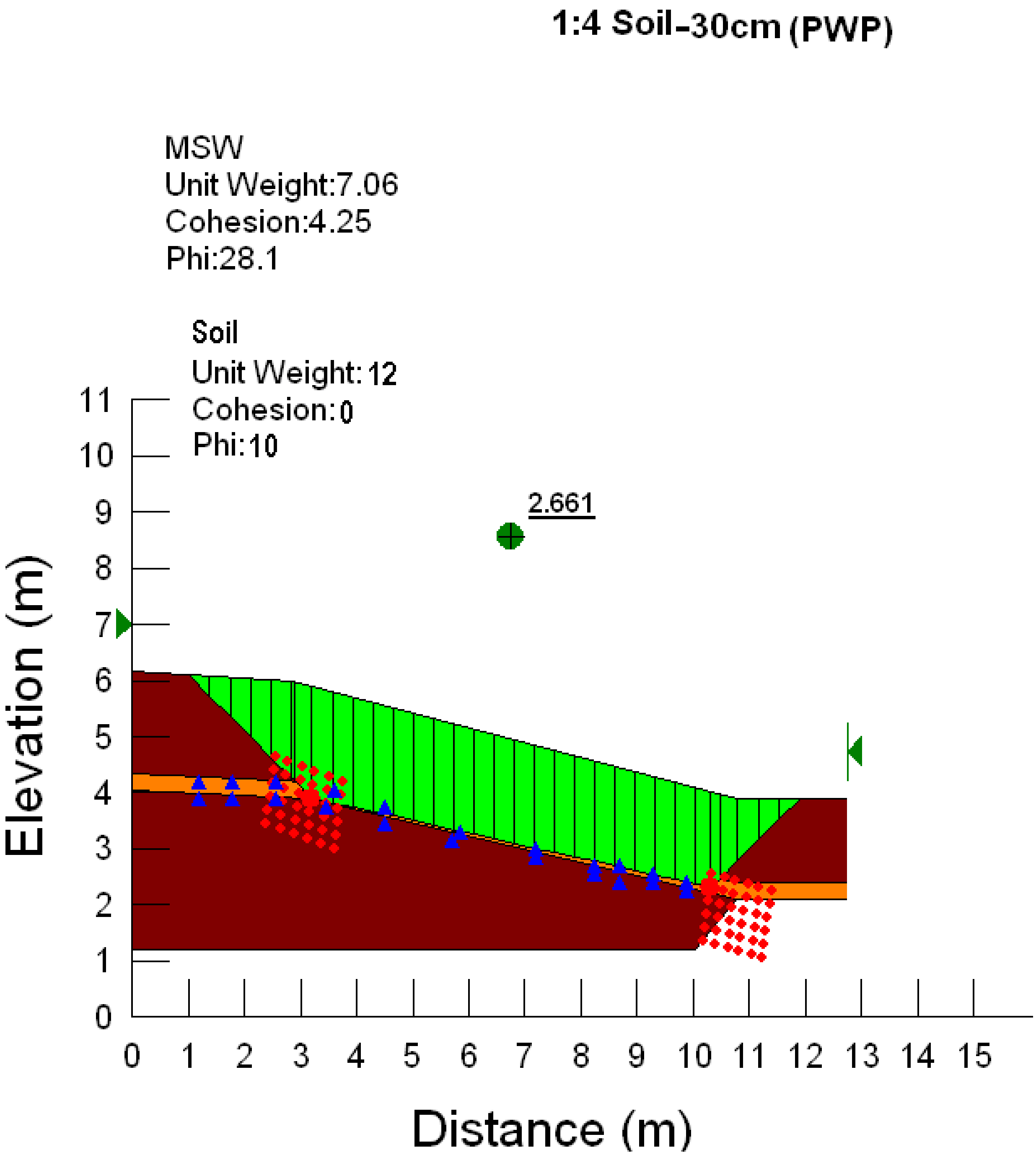

1:4 1Y-Mulch -30cm (PWP)
MSW
Unit Weight:7.06
Cohesion:4.25
Phi:28.1
1Y-Mulch
Unit Weight: 3.2
Cohesion:1
Phi:16
3.822
Elevation (m)
Distance (m)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15



1:4 Fresh Mix-30cm (PWP)
MSW
Unit Weight:7.06
Cohesion:4.25
Phi:28.1
Fresh Mix
Unit Weight: 5.6
Cohesion:1
Phi:15
3.525
Elevation (m)
Distance (m)

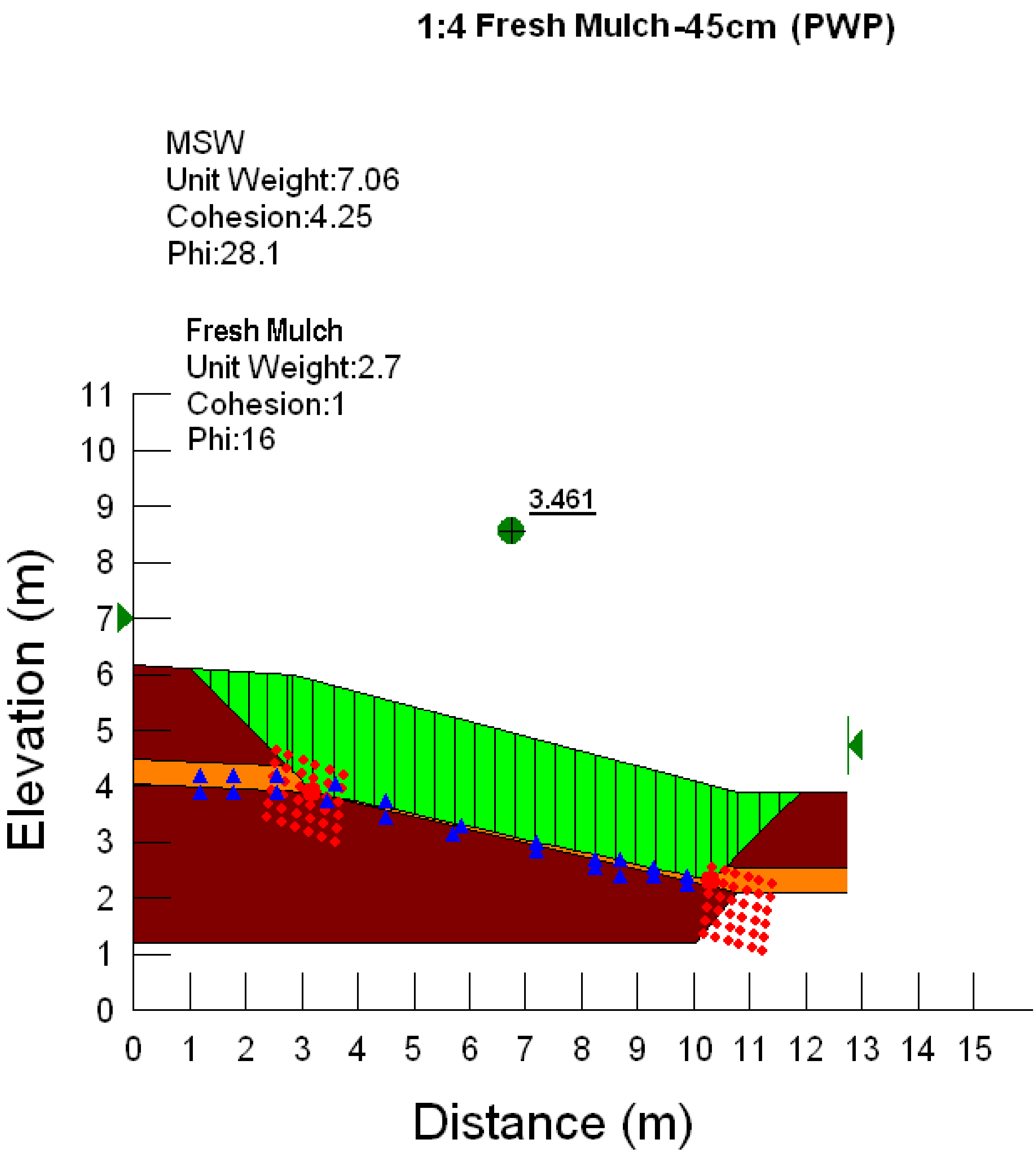

1:4 1Y-Mix-30cm (PWP)
MSW
Unit Weight:7.06
Cohesion:4.25
Phi:28.1
1Y-Mix
Unit Weight: 6.7
Cohesion: 0
Phi: 12
3.223
Elevation (m)
Distance (m)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

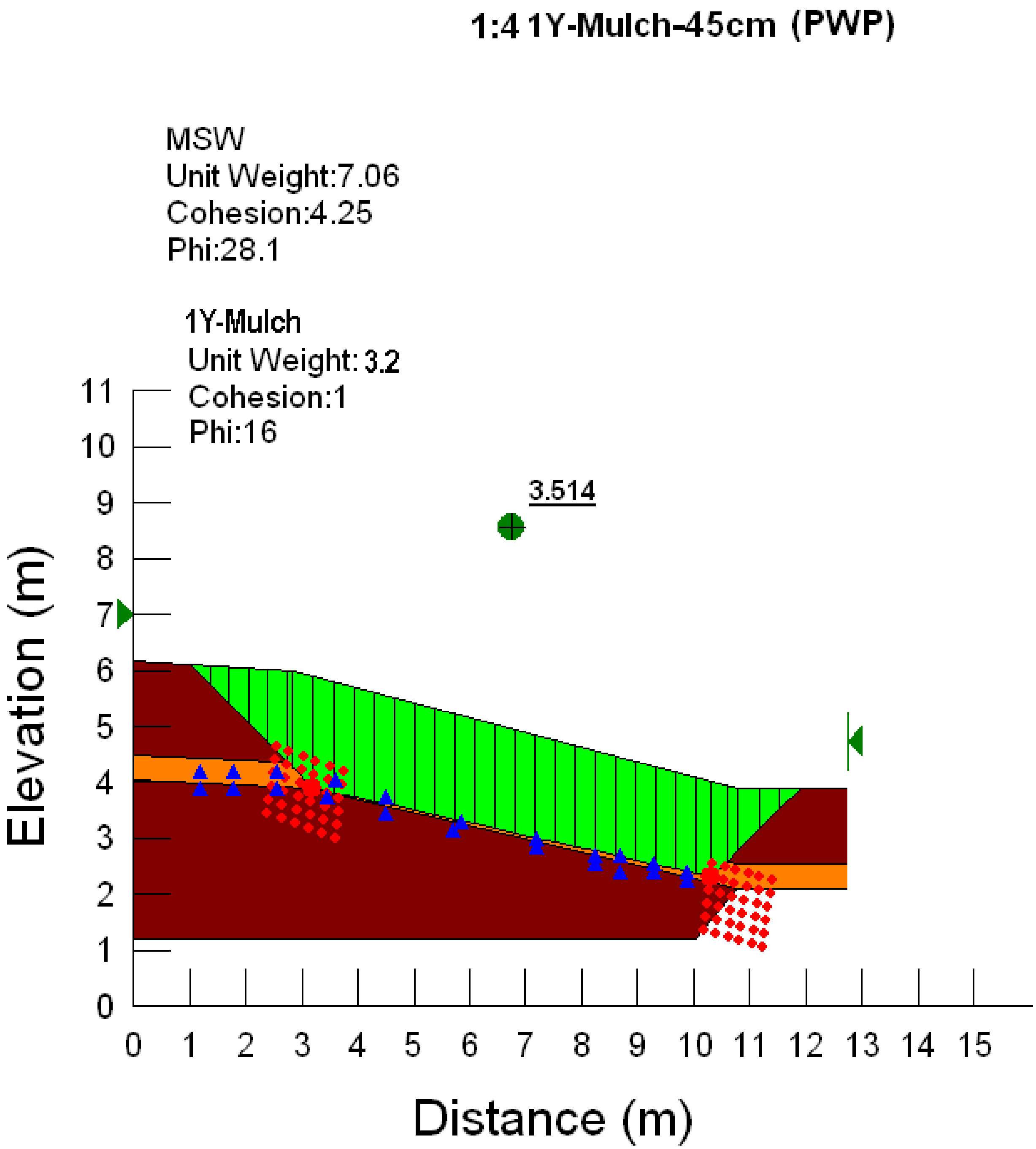

1:4 3Y-Mix-30cm (PWP)
MSW
Unit Weight:7.06
Cohesion:4.25
Phi:28.1
3Y-Mix
Unit Weight: 9.4
Cohesion: 0
Phi: 11
2.995
Elevation (m)
Distance (m)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

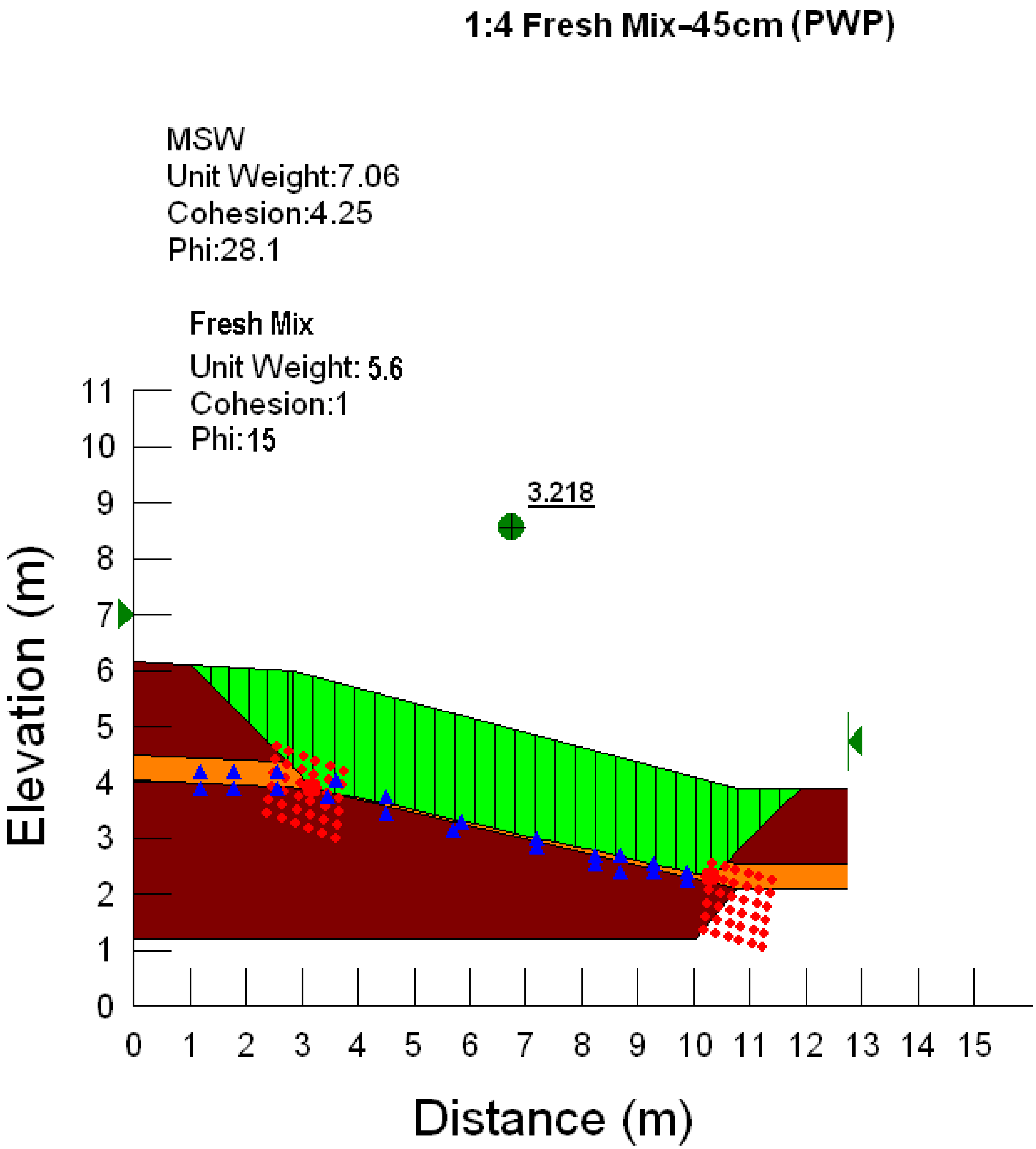


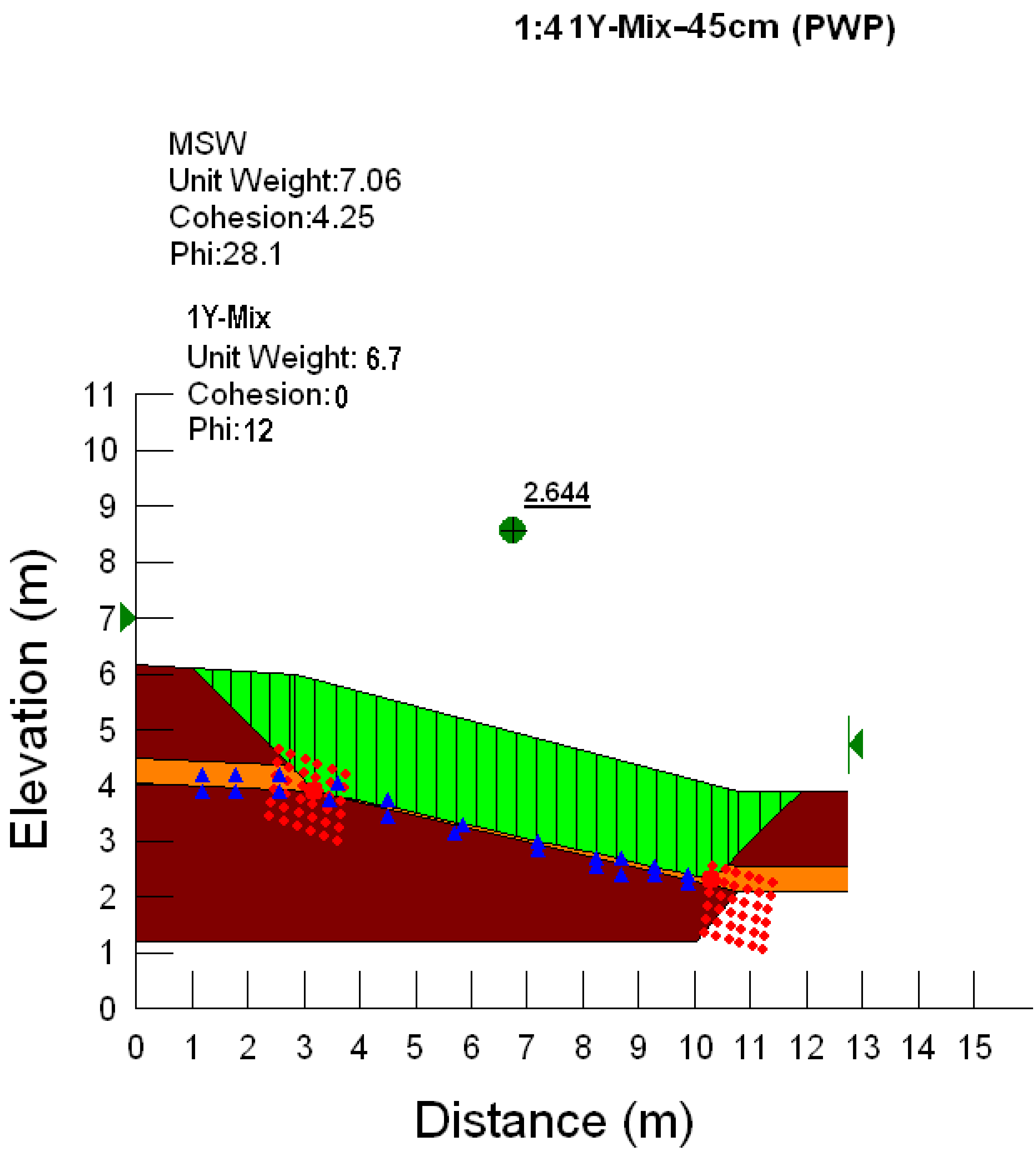
1:4 Soil-30cm (PWP)
MSW
Unit Weight:7.06
Cohesion:4.25
Phi:28.1
Soil
Unit Weight: 12
Cohesion: 0
Phi: 10
2.661
Elevation (m)
Distance (m)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

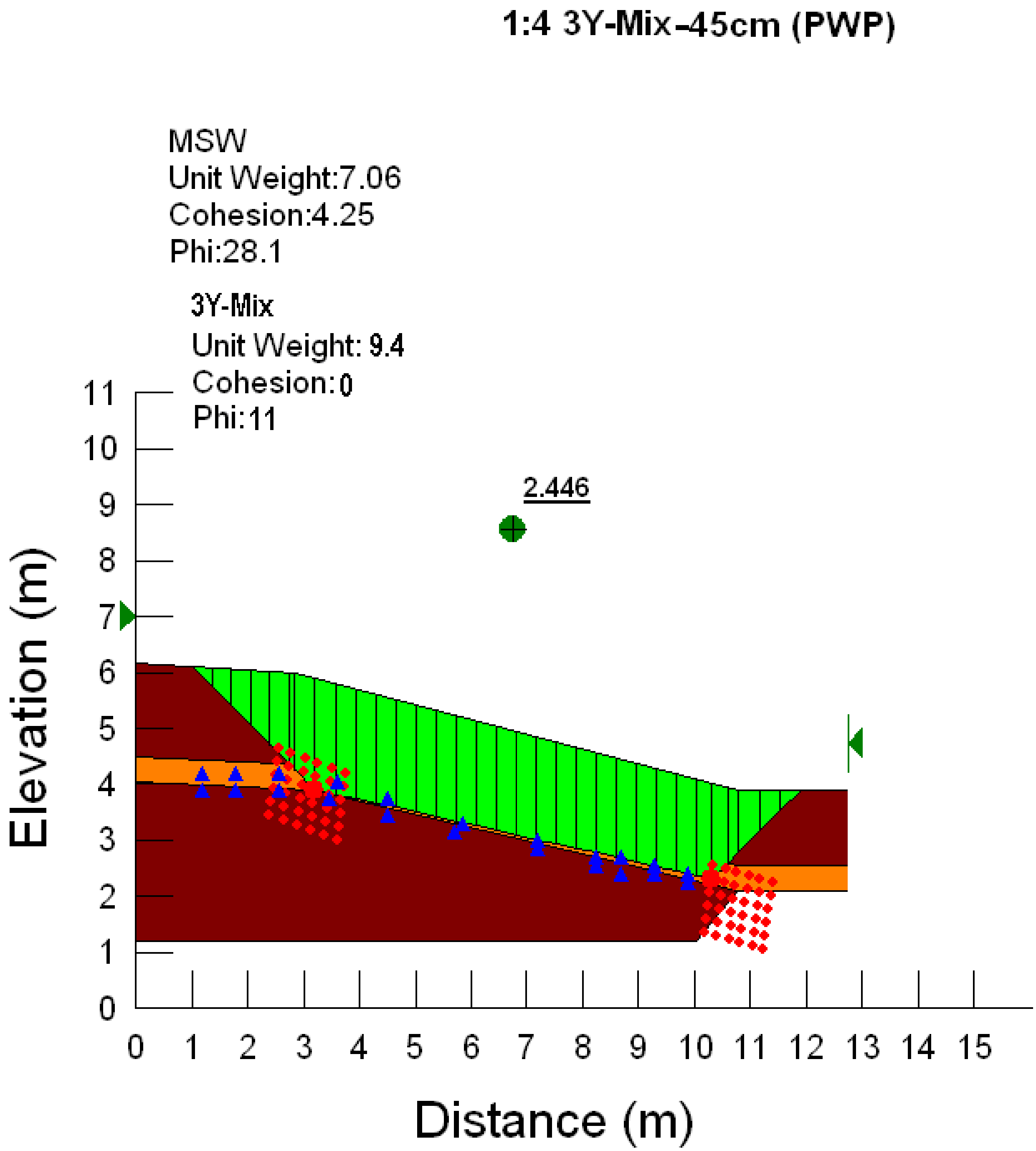
Block Failure/PWP (Slope 1:4 / Cover Depth = 45cm)

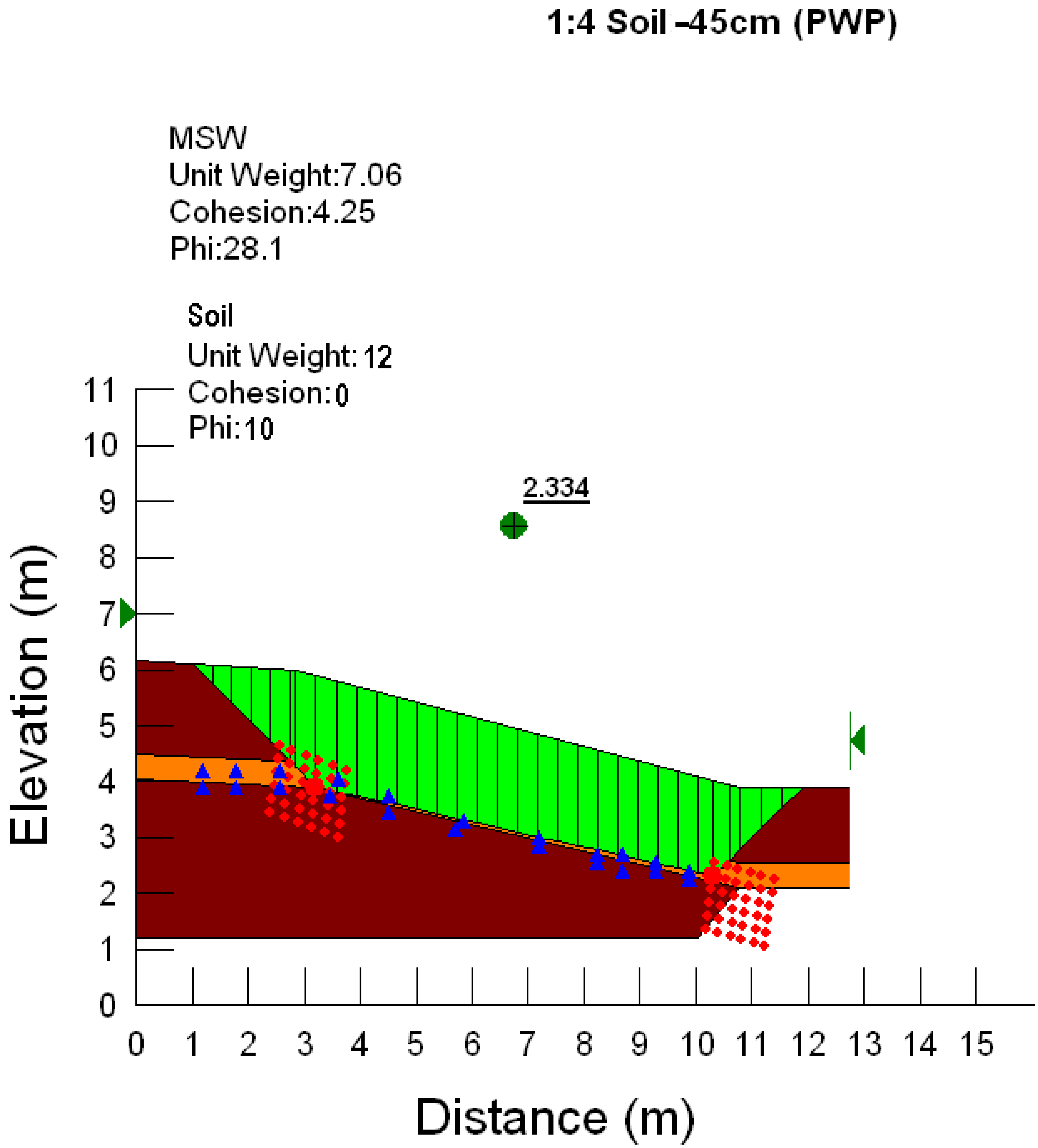



1:4 1Y-Mulch-45cm (PWP)
MSW
Unit Weight:7.06
Cohesion:4.25
Phi:28.1
1Y-Mulch
Unit Weight: 3.2
Cohesion:1
Phi:16
3.514
Elevation (m)
Distance (m)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15


1:4 Fresh Mix-45cm (PWP)
MSW
Unit Weight:7.06
Cohesion:4.25
Phi:28.1
Fresh Mix
Unit Weight: 5.6
Cohesion:1
Phi:15
3.218
Elevation (m)
Distance (m)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15


1:4 1Y-Mix-45cm (PWP)
MSW
Unit Weight:7.06
Cohesion:4.25
Phi:28.1
1Y-Mix
Unit Weight: 6.7
Cohesion:0
Phi:12
2.644
Elevation (m)
Distance (m)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15


1:4 3Y-Mix-45cm (PWP)
MSW
Unit Weight:7.06
Cohesion:4.25
Phi:28.1
3Y-Mix
Unit Weight: 9.4
Cohesion: 0
Phi: 11
2.446
Elevation (m)
Distance (m)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15



1:4 Soil -45cm (PWP)
MSW
Unit Weight:7.06
Cohesion:4.25
Phi:28.1
Soil
Unit Weight: 12
Cohesion: 0
Phi: 10
2.334
Elevation (m)
Distance (m)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

APPENDIX D: LCI SPREAD SHEET

Sequestered carbon for landfilled green waste

	g C-seq/g YW	g CO2-eq/g YW	g CO2-eq/ton YW	Weight Percentage	g CO2-eq/ton YW
Grass	**0.24**	0.88	880,000	5	44,000
Leaves	**0.47**	1.72	1,723,333	5	86,167
Branches	**0.38**	1.39	1,393,333	90	1,254,000
Total				100	1,384,167

Sequestered carbon for composted green waste

	g C-seq/g FYW	g C/g YW	g CO2-eq/g YW	g CO2-eq/ton YW
Yard Waste	**0.02**	0.01	0.37	37,000