HEAP LEACH FACILITY LINER DESIGN

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ABSTRACT

Heap leach facility liner designs have evolved significantly over the last twenty years. In the past, many heap leach liner designs tended to follow a “cookbook” approach without much consideration given to the interaction between the various components such as the foundation, underliner, geomembrane, overliner, and collection piping. It is now generally recognized that the approach to liner design should take into account the behavior of all of the materials that make up the liner system, including materials above the liner such as the solution collection piping, and air injection piping.

The advancements in liner design approach have been driven by several factors, including:

- Advancements in our understanding of the long-term response of geosynthetics under high loads and very harsh environmental conditions;
- The design, construction, and operation of heap leach facilities with significant ore loads [approaching 3 Mega-Pascals (MPa)];
- The construction and operation of very large leach pads that span distances of 5 kilometers across varying foundation materials;
- Improvements in understanding solution collection techniques for better recovery and pipe performance; and
- The commitment of mining companies to local, national, and international environmental standards.

This paper presents an overview of current leach facility liner design approach. Issues, such as the interaction between the various liner design components, are discussed. General guidelines are also presented and discussed.

INTRODUCTION

A critical component to the operation of a heap leach facility is the liner system. When properly designed and constructed, a liner system is an environmental and operational benefit to the facility by providing hydraulic containment of leach solutions within the facility while enhancing solution recovery. In the past, liner systems were somewhat designed following a “cookbook” approach without much consideration given to the interaction between the various components such as the foundation, underliner soils, geomembrane, overliner materials, and collection piping.
Over the past twenty years, our understanding of the design of liner systems for heap leach facilities has evolved in response to several factors, some of which include:

- Advancements in our understanding of the long-term response of geosynthetics under high loads and very harsh environmental conditions;
- The design, construction, and operation of heap leach facilities with significant ore loads (approaching 3 MPa);
- The construction and operation of very large leach pads that span distances of 5 kilometers across varying foundation materials;
- Improvements in understanding solution collection techniques for better recovery and pipe performance; and
- The commitment of mining companies to local, national, and international environmental standards.

It is now generally recognized that the approach to liner design should take into account the behavior of all of the components that make up the liner system including:

- Foundation materials;
- Underliner soils;
- Geomembrane liner;
- Overliner materials (drainage and/or protection layers); and
- Solution collection/air injection piping.

Traditionally, the solution collection and air injection piping networks were not considered part of the liner system. However, these piping networks are typically bedded within the overliner materials (drainage and/or protection layers) which are in direct contact with the geomembrane liner. Since the overliner materials have a significant influence on pipe performance under load the design of the overliner materials must be compatible with the geomembrane liner and the solution collection/air injection piping.

This paper presents a discussion on the design of liner systems for heap leach facilities. The primary focus of this paper is the development of a design that considers the behavior and interaction of the various components of the liner system.

**GENERAL LINER SYSTEM CONFIGURATIONS**

Heap leach facility liner system configurations vary depending on the type of leach facility (single-use pad, on-off, or valley leach), site conditions (topography, climate, construction materials), and ore type. In general, liner systems configurations can be described as either single-composite or double-composite liner systems, as illustrated in Figures 1 or 2.

Single-composite liner systems are generally utilized in areas where leach solution hydraulic heads are low (less than a few meters) and consist of the following components:

- Prepared foundation;
- Underliner;
• Geomembrane liner; and
• Overliner layer with piping.

Double-composite liner systems are generally used in areas with high leach solution hydraulic heads (such as solution collection areas in valley leach designs). The purpose of the double-composite liner is to reduce the hydraulic head on the lower geomembrane, thereby minimizing leakage from the facility. A discussion on the performance of double-composite liner systems is presented in Bonaparte and Gross (1990).

The components of a double-composite liner system consist of the following:

- Prepared foundation;
- Underliner;
- Secondary geomembrane liner;
- Leak detection and recovery layer;
- Primary geomembrane liner; and
- Overliner layer with piping.

Depending on the type of ore and leaching process, the overliner layer may consist of the following configurations:

- Single, permeable drainage layer with or without solution collection piping;
- Compacted, low permeability protection layer overlain by permeable drainage layer with solution collection piping; and
- Single, permeable drainage layer with solution collection piping, overlain by a permeable protection layer with or without air injection piping.

Other variations in the overliner configuration have also been used to suit local conditions, processing requirements, or type of leach facility. For example, for the design of on-off leach pads, a thick sacrificial layer may be placed as part of the overliner to prevent liner damage when ore is removed.

LINER SYSTEM COMPONENTS

The following sub-sections provide detailed discussion on the various components of leach facility liner system, as shown in Figures 1 and 2.

Foundation

One of the most important aspects of liner system design is the condition of the foundation and foundation materials. The ideal foundation is one that consists of homogeneous, firm materials. A firm foundation is desirable to minimize settlements under loads which would translate to strain on the geomembrane liner and the piping networks in the overliner. However, ideal foundation conditions are seldom encountered in mine sites that may be located anywhere from the high Andean mountains of South America to the marshlands in central Asia.
Characterization of the foundation conditions requires a thorough geotechnical investigation, which typically consists of drilling geotechnical borings and excavation of test pits. Where needed, geophysical methods (seismic, electrical, magnetic) may be required to provide spatial coverage at challenging sites. The geotechnical investigation may also include in-situ testing, such as Standard Penetration Tests (SPT’s), Cone Penetration Tests (CPT’s), and shear vane test to characterize the subsurface materials. Samples of foundation materials are also collected and tested under triaxial compression, direct shear, and one-dimensional compression/consolidation to assess the foundation response under the anticipated heap facility loads.

As part of the liner system design, foundation settlement analyses are conducted using either analytical or numerical methods to quantify the potential settlement resulting from ore loads. If groundwater is also present in the foundation, settlements due to seasonal variation or groundwater extraction must also be estimated. The calculated foundation settlements are typically integrated into the grading plan for the heap leach facility. This allows the designer to specifically address areas that have problematic settlement. In some cases, soft foundation materials may be removed or the treated (e.g. preloaded) to address settlement. In other cases, the facility geometry may be modified to address settlement.

Integration of foundation conditions and settlement into the grading plan is an iterative exercise. When changes are made in the grading plan to address specific foundation conditions, the geometry of the heap leach facility may also require modification, which would change the settlement calculations. For example, if the slope of the pad floor is increased to accommodate future settlements, the new floor slope may impact the stability of the ore on the pad, requiring adjustments to the ore stacking plan; thereby changing the settlement calculations.

The iterative grading plan earthworks must also be analyzed with a focus on constructability and economic considerations. These analyses may lead to additional changes in the facility geometry, requiring more iterations on foundation settlement and geomembrane strains.

**Underliner**


If possible, the underliner should consist of fine-grained soils with the following characteristics:

- Maximum particle size - 38 mm
- Non-gap graded particle size distribution
- Moderate to high fines (minus 200 mesh) content
- Moderate plasticity
- Saturated hydraulic conductivity of $1 \times 10^{-6}$ cm/sec or less

Figure 3 shows a typical particle size range used for underliner soils. The particle size range shown in Figure 3 is presented as a general guide, and should not be used as a substitute for soil characterization, as discussed below.

Where possible, a native soil should be used as the underliner to minimize construction costs. Borrow sources for the underliner soil must be fully characterized to define the mechanical and hydraulic characteristics of the material. Characterization programs may the following standard tests: gradation; Atterberg limits; compaction (modified or standard Proctor); triaxial compression; and permeability under varying compaction.

In some projects, bentonite admixtures may be used to achieve a suitable, low permeability liner bedding soil to minimize potential seepage. If used, the bentonite material should be tested for compatibility with the native soils and the anticipated leach solution chemistry. Geosynthetic Clay Liners (GCL) may also be used as a substitute to the underliner. However, if use of a GCL is contemplated, detailed engineering evaluations must be conducted to assess the stability of the GCL under the anticipated loading and considerations need to be made to address creep deformation, compressibility, and internal shear strength. GCL’s should not be used in areas subject to high shearing loads.

In typical liner system designs, the underliner is specified as 0.3 m thick (compacted thickness), depending on permeability and seepage requirements, and construction considerations. It should be noted that if the surficial foundation soils meet the criteria for an underliner, then the surficial soils may be scarified and compacted to form the underliner.

Since the underliner is in direct contact with the geomembrane, internal and interface shear strength of the underliner are very important. The design of the underliner material is a balance between permeability and shear strength. These aspects are discussed in the following section.

**Geomembrane Liner**

The geomembrane liner is the primary component in a liner system. Common geomembrane liner materials used in the design of heap leach facilities include Linear Low Density Polyethylene (LLDPE), High Density Polyethylene (HDPE), and Polyvinyl Chloride (PVC), with the majority of facilities being constructed using LLDPE and HDPE. When selecting a geomembrane type, it is important to consider all of the properties of the liner with respect to the anticipated loading conditions, local climatic conditions, experience of installation crew, and local construction conditions. In addition, the thickness and type of geomembrane liner should consider the following factors:

- Foundation settlement and maximum strain;
- Anticipated ore loads;
- Underliner material characteristics (maximum particle size, internal, and interface friction);
- Overliner material characteristics (maximum particle size, internal, and interface friction); and
- Slope stability requirements for the facility.

Table 1 provides general guidance on liner type and thickness for various mining applications. It is important to note that the information presented in Table 1 should be used as a general guide and not a substitute for testing and design.

### Table 1 - Geomembrane Selection General Guide

<table>
<thead>
<tr>
<th>Foundation Condition</th>
<th>Underliner</th>
<th>Overliner</th>
<th>Effective Stress at Liner (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>&lt; 1.2</td>
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<tr>
<td>Firm</td>
<td>Coarse</td>
<td>Coarse</td>
<td>2 mm LLDPE or HDPE</td>
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<td></td>
<td></td>
<td>Fine</td>
<td>2.5 mm LLDPE or HDPE</td>
</tr>
<tr>
<td></td>
<td>Fine</td>
<td>Coarse</td>
<td>1.5 mm LLDPE or HDPE</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fine</td>
<td>2 mm LLDPE or HDPE</td>
</tr>
</tbody>
</table>

| Soft | Coarse     | Coarse    | 2 mm LLDPE                     |
|      |            | Fine      | 2.5 mm LLDPE                   |
|      | Fine       | Coarse    | 2 mm LLDPE                     |
|      |            | Fine      | 2.5 mm LLDPE                   |

|                       |            | Fine      | 1.5 mm LLDPE                   |
|                       |            |           | 2.5 mm LLDPE                   |

**Notes:**
1. Underliner refers the material directly beneath the geomembrane (primary geomembrane for double composite systems). Coarse or fine refers to the general gradation. Testing and design calculations are required to assess impacts on geomembrane.
2. Overliner refers the material directly above the geomembrane (primary geomembrane for double composite systems). Coarse or fine refers to the general gradation. Testing and design calculations are required to assess impacts on geomembrane.
3. Foundation conditions are presented in relative stiffness. Testing and design calculations are required to assess foundation impacts on geomembrane.
As discussed previously, foundation settlement must be considered in geomembrane selection as it may give rise to large liner strains. Giroud and Soderman (1995) present a theoretical analysis on the performance of various geomembranes subjected differential settlement. This study illustrates that geomembrane materials with low elastic moduli may be better suited in applications where high differential settlements are anticipated. The selected geomembrane type should be compatible with the anticipated foundation settlement.

**Liner-Load Testing**

Selection of geomembrane liner thickness may be derived using a theoretical approach such as that presented in Giroud et al (1995). However, there are numerous factors that can lead to liner puncture that cannot be taken into account in a theoretical approach. These factors may include:

- Varying loading conditions at the geomembrane surface (hydrostatic, point load, shearing, etc);
- Long term creep of the geomembrane at point loads; and
- Stress cracking.

More often, the geomembrane liner thickness and type for a particular application is evaluated by conducting a series of liner load tests, whereby representative soil materials (overliner and underliner) and the proposed geomembrane liner are constructed according to anticipated specifications and configuration, and loaded to the expected maximum loads to evaluate the performance of the liner.

A schematic of a load-testing frame used for liner testing is shown in Figure 4. The testing frame consists of a rigid vessel with a loading ram and platens. The liner system design under consideration (single composite/double composite) is constructed within the vessel and loaded. The maximum test load is generally sustained for a minimum of 24 hours. Upon completion of the test, the geomembrane liner is inspected for punctures, both visually and by applying a vacuum (vacuum pressure of 70 mm Mercury [Hg]).

It is important to note that this frame differs from those presented in American Society for Testing and Materials (ASTM) methods D5514 and D5617. The frame in Figure 4 is suggested because it subjects the liner to confined loads, which are more likely to occur in the heap leach facility.

An important key to liner-load testing is to include conditions which may occur in the field, such as rock particles on the underliner surface or directly on the liner surface. Figure 5 illustrates a condition that commonly occurs in the field. This illustration shows the presence of isolated rocks on the underliner surface and in the overliner. Many of the leaks that develop in heap leach facilities are related to rock particles left on the underliner surface or that have collected at the bottom of the overliner. As the leach pad is loaded with ore, point loads (from the rock particles) develop on the geomembrane surface, resulting in puncture. For liner-load tests, rock particles are manually placed on underliner surface and directly on the geomembrane to simulate these field conditions. The rock particles placed on the underliner surface and the
geomembrane should represent the maximum particle size that is specified for each material (underliner or overliner).

Figure 6 presents a liner-load test with rocks placed on the underliner surface. Figure 7 presents the resulting deformed liner (1.5 mm LLDPE) after loading to 0.9 MPa. In this test the liner passed without puncture, even though the liner was highly deformed.

Liner-load tests are also used to design of the gradation specification for drainage and leak detection layers. Figure 8 presents a photograph of 2.5 mm LLDPE exposed to an equivalent load of 240 m of ore (i.e., 4.3 MPa) with a double-composite liner design. The overliner material consisted of minus 38 mm diameter material, while the underliner (or leak detection layer) consisted of minus 25 mm diameter material. This liner sample failed the liner load test as a result of the high loads combined with a leak detection layer that was too coarse (low sand fraction). The results of this test were used to refine the leak detection layer gradation. Subsequent testing of the geomembrane with the refined leak detection layer successfully sustained the load equivalent to 240 m of ore.

**Interface Shear Testing**

In addition to liner-load testing, interface shear testing (ASTM D5321) is also required to evaluate the stability of the liner system under the anticipated ore loading conditions. The interface tests are often tested using a “floating” configuration of liner bedding soil / geomembrane / overliner (drainage layer). It is recommended that the liner interface shear tests be conducted after the normal stress has been applied for a minimum of 24 hours. This allows the liner system to “seat” prior to shearing.

It is important that the tests are conducted based on the anticipated conditions in the field, i.e., the test specimen should be representative of final construction by using the soils planned for underliner and overliner construction, as well as the specific geomembrane liner material planned for construction. For example, the liner bedding soil and drainage layer materials should be placed and compacted within the specifications for the project. In addition, if the drainage layer materials are anticipated to degrade or decompose over time, then these materials should be included in the test. The range of shear strength for interface shear may vary considerably, even within soils that appear to be similar.

Figure 9 presents some ranges of residual friction values from typical interface shear tests. For heap leach facilities, the stability should be evaluated using residual interface shear strengths. Residual strengths are used because during overliner placement and ore loading, the overliner is likely to undergo displacement along the geomembrane interface, thereby mobilizing post-peak shear strength. The data shown in Figure 9 is for illustration purposes only; actual testing is required to define the appropriate frictional properties for design.

**Overliner Materials**

Depending on the type of ore and leaching process, the overliner layer may consist of the following configurations:
• Single, permeable drainage layer with or without solution collection piping;
• Compacted, low permeability protection layer overlain by permeable drainage layer with solution collection piping; and
• Single, permeable drainage layer with solution collection piping, overlain by a permeable protection layer with or without air injection piping.

**Drainage Layer**

The drainage layers are typically constructed of native or processed granular materials. Granular materials are preferred for these layers due to the need to maintain permeability under high loads and the need for high internal shear strength and interface shear strength. The drainage layer has two purposes, protecting the geomembrane from damage from ore loading (if placed directly against the geomembrane) and to protect the solution collection piping network from crushing.

The material for the drainage layer must be graded to achieve the desired permeability and shear strength properties, while minimizing damage to the geomembrane liner. In addition, the drainage layer material gradation needs to have a stiffness and arching capacity that is compatible with the solution collection piping. The important interaction between the drainage layer and solution collection pipe stability is discussed in Lupo (2001), Lupo et al (2003), and Lupo et al. (2005). A discussion on the interaction between the drainage layer and solution collection piping is presented later in this paper.

If available, the drainage layer should consist of rounded gravels, coarse sands, or well-graded crushed ore with the following characteristics:

- Maximum particle size - 33 mm
- Non-gap graded particle size distribution
- Low fines (minus 200 mesh) content
- No plasticity
- Saturated hydraulic conductivity of $1 \times 10^{-2}$ cm/sec or greater

Figure 10 presents ranges of particle size gradation curves for drainage layer materials. The range of gradations shown in Figure 10 should be used as a general guide and not a substitute for actual testing and design.

As indicated, if the drainage layer is placed directly against the geomembrane, then the design and gradation of that layer must be compatible with both the geomembrane (e.g. liner-load and interface shear tests) and the solution collection piping. If the drainage layer is not located directly on the geomembrane, then its design only needs to be compatible with the solution collection piping.
**Protection Layers**

Protection layers may be used either directly on the geomembrane or over a drainage layer. If the protection layer is placed over the geomembrane, it is used to protect the geomembrane from the drainage layer. This approach may be used if the drainage layer gradation is very coarse and cannot be placed directly on the geomembrane without damaging it. In this scenario, the protection layer design should focus on protection of the geomembrane while providing sufficient interface shear for stability of the leach pad. Permeability of the protection layer is not an important design issue. The design of the protection layer requires both liner-load and interface shear testing to determine the proper gradation and physical characteristics. Typical protection layer (over geomembrane) material may consist of silt, silty sands, or gravelly clays. It is important to note that geotextiles are not often used as protection layers over geomembranes in heap leach facilities. Geotextiles are not often used or have limited use in heap leach facilities because the geomembrane-geotextile interface shear strength tends to be lower compared to native soils and drainage materials.

If a protection layer is placed above the drainage layer, it is used to protect the drainage layer and solution collection pipes from the ore loads. This approach may be used if the cover over the solution collection pipes needs to be increased to improve stress-arching around the pipes (see discussion later in this paper). In this scenario, the protection layer design should focus on having similar permeability and shear strength as the drainage layer, so that solution flow and heap stability are not compromised. Typical protection layer (over drainage layer) material may consist of coarse gravels and crushed or Run-of-Mine ore.

**Leak Detection/Collection Layer**

In double-composite liner systems (Figure 2), a leak detection layer is used to control hydraulic head on the lower geomembrane. Since this material is “sandwiched” between two geomembranes, this material must be carefully selected and graded to achieve the following performance goals:

- Prevent puncture of the upper and lower geomembranes. This can be evaluated by conducting a series of liner-load tests;
- Provide sufficient permeability under load to allow collection of leakage solution, if it occurs;
- Sufficient internal shear strength to maintain heap stability under anticipated loads; and
- Sufficient interface shear strength to maintain heap stability under anticipated loads.

The design of leak detection/collection layers generally follows that used for the design of drainage layers, with similar material types and gradations.
SOLUTION COLLECTION PIPING

Plastic piping (HDPE, polyvinylchloride [PVC], corrugated polyethylene [CPE], etc.) has a wide range of uses in mining applications. For most applications, such as routing of solution in pipes with a shallow burial depth, traditional methods (e.g. the Modified Iowa method [USDA, 1990]), may be used for design. However, plastic piping is increasingly being used in applications with very high loads. Under these conditions, the pipe stiffness is significantly lower than the surrounding material (crushed ore, drainage gravels, etc.).

In heap leach facilities, solution collection pipes may be exposed to ore heights up to 180 m, exposing plastic pipes to stresses in excess of 3 MPa. Plastic underdrain piping beneath heap leach pads may be exposed to burial depths exceeding 200 m. Under these conditions, the design criteria and levels of acceptable pipe performance must be modified from traditional approaches. Figure 11 presents a photograph of a solution collection pipe from a heap leach facility that has undergone over 20 percent crown deflection (note buckling in crown). Although the pipe has undergone high deformation, it continues to operate (as designed) to collect and route process solutions. The pipe shown in Figure 11 is performing acceptably, even though yielding is clearly evident.

Pipe design calculations based on traditional methods are not applicable in these cases as high strain and localized buckling are acceptable. Some notable studies on the performance of plastic pipes under high loads include Watkins (1990), Adams, et al (1988), Moore & Zhang (1998). Traditional methods for pipe design are based on stress theory, whereby the stress conditions within the pipe wall are evaluated based on assumed loading conditions. These design approaches were initially developed for concrete and steel pipe and has been extended for polyethylene pipe design. The stress theory method was developed assuming the pipe materials are very stiff compared to the pipe envelope material (the material surrounding the pipe). Under these conditions, the loads are carried entirely by the pipe, not by the pipe envelope.

Figure 12 presents pipe deflection versus burial depth data from the open literature. Lupo (2001) presented an approach for analyzing HDPE pipe under very high loads. This approach for flexible pipe design was based on the work of Burns & Richard (1964) and Höeg (1968), however the soil arching component has been modified to account for rotational stresses. The flexible pipe equations include the interaction of the pipe with the surrounding material. The solutions presented by Burns & Richard and Höeg assume both the pipe and soil have constant properties and are linear elastic. These simplifications can limit the usefulness of these equations for flexible pipe design because both the pipe and pipe envelope materials behave non-linearly under compression. To provide a more suitable solution for flexible pipe, the Burns & Richard solution was modified to account for nonlinear compression of the pipe envelope, viscoelastic nature of the polyethylene pipe material, and stress arching in pipe envelope materials.

Figures 13 and 14 present the analytical model results compared to actual measured pipe performance. As shown, the modified pipe equations agree well with actual pipe performance. It is important to note that the analytical model assumes the pipe envelope thickness is sufficient to support stress arching over the pipe. The thickness of the envelope is a function of the material properties of the envelope materials.
Based on field studies from actual heap leach facilities combined with back-calculation of pipe performance, the following guidelines have been developed for pipe design:

- Non-pressurized HDPE pipes appear to undergo severe deformation and buckling once the crown deflections exceed 20 percent. For design, a maximum crown deflection of 15 percent may be used provided consideration is given to the reduction in flow area due to high crown-deflection;
- The pipe envelope design (drainage layer) is as important as the pipe design and pipe selection. The drainage layer should be designed to promote arching within the fill. Drainage layer materials with low stiffness tend to transmit loads into pipe resulting in high deformation. Drainage layer materials with high stiffness tend to promote arching and transmit only a portion of the load to the pipe. The drainage layer material stiffness can be tested using simple one-dimension compression tests;
- Pipe material types, thickness, and ring-stiffness should be selected to be compatible with the drainage material. A pipe with a ring-stiffness greater than the drainage layer stiffness will tend to take more stress, therefore the pipe section and material properties need to be compatible with the higher stress level. A pipe with a ring-stiffness lower than the drainage material stiffness will deform significantly, therefore the pipe material must be selected to allow high deformation without brittle failure; and
- For initial design, the pipe envelope thickness should be sized to be two times the pipe diameter. This thickness apparently allows arching within the envelope to develop and support part of the applied load. The envelope thickness will vary depending on the material used for the envelope.

Closure

This paper has presents a general review of liner system design for heap leach facilities. Issues discussed include:

- The design approach to address interaction of the various materials used for the liner system;
- Material recommendations for the underliner, geomembrane, and overliner (drainage and protection layers);
- Recommended testing methods for the geomembrane to verify compatibility with the underliner and overliner materials; and
- The interaction between the solution collection piping and air injection piping with the overliner materials and the liner system design.

The methods presented herein should be used as a general guide to standardize liner system design for heap leach facilities.
REFERENCES


Figure 1. Typical single-composite liner design.
Figure 2. Typical double-composite liner design.
Figure 3. Typical underliner gradation envelope.
Figure 4. Liner-load test frame schematic.
Figure 5. Typical field condition.
Figure 6. Rocks placed prior to liner load test.

Figure 7. Deformed liner after test (0.9 Mpa normal stress).
Figure 8. Failed liner after liner-load testing.
Figure 9. Residual interface friction angles.

Figure 10. Typical overliner gradation envelope.
Figure 11. Deformed solution collection pipe - 20% crown deflection.
Figure 12. Measured crown deflection - plastic pipes under load.
Figure 13. Predicted solution collection pipe response.

Figure 14. Predicted solution collection pipe response - soil arching.