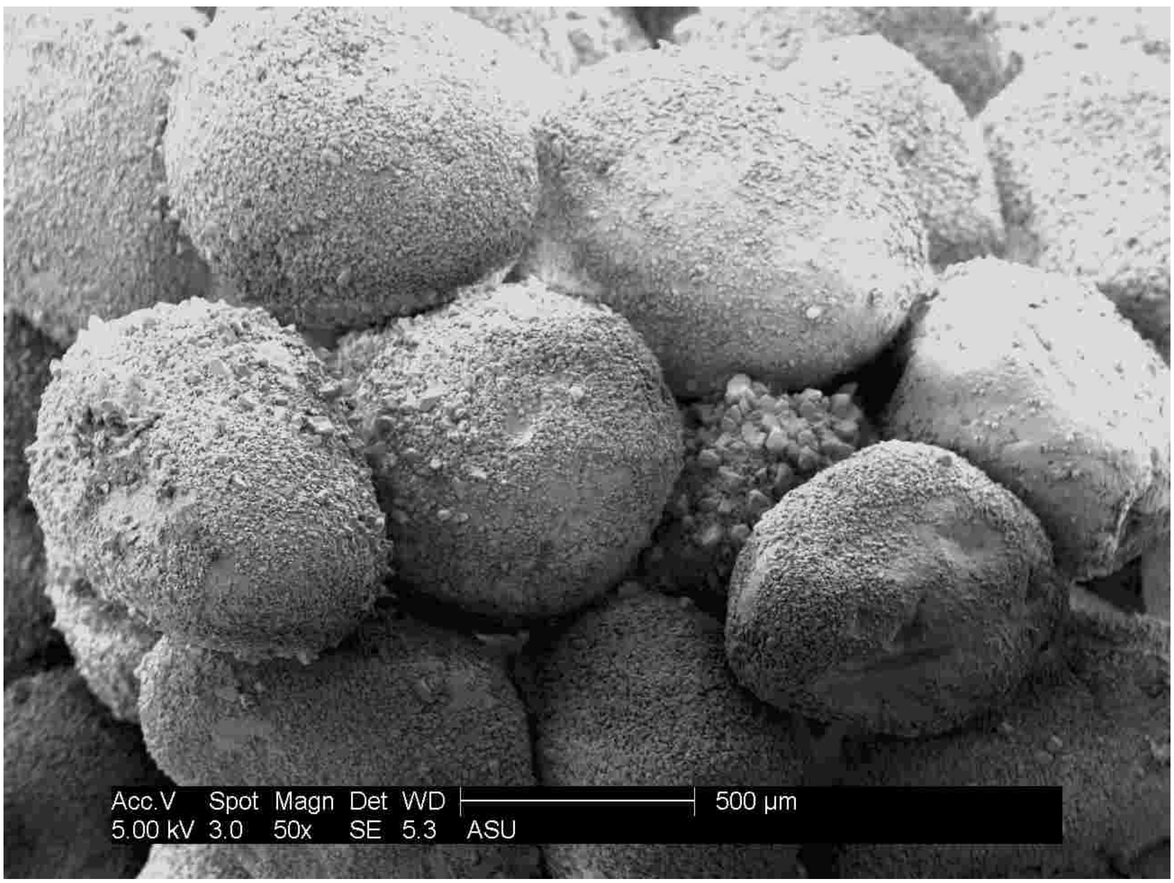
RECLAMATION

Managing Water in the West

Bio-Barriers for Seepage and Internal Erosion Control

Research and Development Office
Science and Technology Program
(Final Report) ST-2018-1833-01



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6. AUTHOR(S) Angel Gutierrez, agutierrez@usbr.gov, (928) 343-8371 Rusty Williams, rwilliams@usbr.gov, (928) 343-8351 John Fleming, jfleming@usbr.gov, (928) 343-8356		**5d. PROJECT NUMBER** ST-2018-1833-01
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Bio-Barriers for Seepage and Internal Erosion Control

ANGEL GUTIERREZ Digitally signed by ANGEL GUTIERREZ Date: 2019.03.27 10:07:51 -07'00'

Prepared by: Angel Gutierrez, Ph.D.
Civil Engineer, Facilities Engineering Group, Yuma Area Office

JOHN FLEMING Digitally signed by JOHN FLEMING Date: 2019.03.27 11:52:00 -07'00'

Checked by: John Fleming, Ph.D.
Hydrologist, Water Systems Engineering Group, Yuma Area Office

SAMUEL GARCIA Digitally signed by SAMUEL GARCIA Date: 2019.03.27 19:40:26 -07'00'

Peer Review: Samuel Garcia, P.E.
Civil Engineer, Facilities Engineering Group, Yuma Area Office

CARRIE SCOTT Digitally signed by CARRIE SCOTT Date: 2019.03.28 12:55:47 -07'00'

Peer Review: Carrie Scott, P.E., P.M.P.
Chief, Technical Support Office, Yuma Area Office

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Acronyms and Abbreviations

BOR	Bureau of Reclamation
EICP	Enzyme-Induced Carbonate Precipitation
FHWA	Federal Highway Administration
FY	Fiscal Year
HDPE	High-Density Polyethylene
LC	Bureau of Reclamation, Lower Colorado Region
MICP	Microbially-Induced Carbonate Precipitation
MIDP	Microbially-Induced Desaturation and Precipitation
O&M	Operations and Maintenance
QA/QC	Quality Assurance/Quality Control
SEM	Scanning Electron Microscope
UV	Ultraviolet

Executive Summary

Seepage leading to internal erosion is a major concern for the stability, safety, and reliability of water conveyance and water retaining structures. In addition, droughts across areas of the United States are straining water reservoirs and are requiring operating entities to enhance water conservation by limiting water losses as much as possible. Conventional methods for mitigating seepage and internal erosion can be mainly grouped into two categories: liners/blankets and soil improvement methods. The current methods tend to be costly and require major construction, which tend to be unfeasible due to operational constraints, or can cause significant environmental impacts. Bio-barriers, a state-of-the-art concept, could potentially be less costly, more environmentally friendly, and have little to no impact to operations. A literature review was completed to analyze current conventional methods, ongoing research in bio-barriers, and how bio-barriers could potentially be implemented in Reclamation facilities. A short list of Reclamation facilities that have seepage issues in the Lower Colorado Region was also compiled. These facilities could potentially be targeted as future test sites. The work completed demonstrated that bio-barriers show promise as a possible method for mitigating seepage and internal erosion in the future.

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Introduction

The Bureau of Reclamation's (Reclamation) mission is managing water in the West. Reclamation has a large number of water-conveyance and water-retaining structures (facilities) whose main purpose is to distribute water across the West in an efficient and sustainable manner. However, many of these facilities were built in the early 1900s and are now experiencing significant deterioration and reliability loss either due to their age, poor operation, and/or maintenance protocols (O&M) throughout the years. Deterioration usually increases the possible failure modes of facilities. One of the main failure modes analyzed in most of Reclamation's facilities is embankment failure due to internal erosion.

In addition, droughts across areas of the United States are straining water reservoirs and are requiring operating entities to enhance water conservation by limiting water losses as much as possible. Reclamation is currently working with water districts and stakeholders in the Lower Colorado Region (LC) on a drought contingency plan as water reservoirs are projected to reach historic lows in the near future. The LC currently estimates a 57% chance of reaching shortage declaration in fiscal year (FY) 2020; therefore, facilities must be more efficient at retaining and storing water than ever before. One of the ways to reach this goal is by mitigating seepage losses in the aforementioned facilities.

Since many of Reclamation facilities are built include earthen dikes or embankments, a solution to seepage and internal erosion must be found. Conventional methods for mitigating seepage and internal erosion can be mainly grouped into two categories: liners/blankets and soil improvement methods. The current methods tend to be costly and require major construction, which tends to be unfeasible due to operational constraints or significant environmental impacts. Seepage monitoring is also used widely in industry. However, monitoring is not a mitigation method and, therefore, is not covered within this report.

Seepage and internal erosion go hand-in-hand. Therefore, a solution for one could be used as a solution for the other if implemented at the right time. Issues usually begin with seepage. Seepage, in simple terms, is the movement of a liquid (i.e. water) through a porous medium such as a soil mass. Seepage can be further simplified as leakage when talking about water-retaining structures. If left unchecked, seepage could develop into internal erosion if the correct conditions are present. Contributing factors include high differential pressure between downstream and upstream of an embankment, high seepage velocities, erodible material present, etc. Internal erosion can be broken down further into different types. For the purpose of this report internal erosion will refer to three types: piping, progressive erosion, and suffusion.

Researchers have been studying new methods of soil improvement that show promise in significantly reducing seepage and internal erosion. Bio-barriers, a state-of-the-art concept currently being researched worldwide, could potentially be less costly, more environmentally friendly, and have little to no impact to operations compared to current methods.

Current Methods

Current conventional methods that address seepage and internal erosion were grouped into two categories: liners and soil improvement methods. Most of these methods have been around for many years and are well-known within the geotechnical community. The report focuses on methods that Reclamation would readily apply to projects; therefore, only methods that are widely-accepted by government agencies were reviewed. The Federal Highway Administration (FHWA) released the *Ground Modification Reference Manual* which covers many of the soil improvement methods covered in the consequent sections. The methods in FHWA (2017) are considered to be widely accepted by federal agencies.

Concrete liners

One of the main seepage mitigation methods is concrete lining. Concrete lining consists of placing a relatively shallow concrete pad (no less than 2” thick) along the exposed areas of an unlined canal. Seepage through the concrete pad itself can be considered to be negligible. Typically, seepage occurs along joints if they are not prepared properly (i.e. not using water stops) or through cracks as the concrete deteriorates over time. Reclamation uses concrete-lining in many of its projects and this approach has been shown to result in significant reductions in seepage losses from canals.

An example of the benefit of concrete lining as a seepage mitigation method is the lining of the Coachella Canal in California. The Coachella Canal, originally built in 1948, crosses through the Imperial East Mesa, more commonly known as the Imperial Sand Dune area. The soils, mostly coarse cohesionless sands, have a high hydraulic conductivity. The canal was originally unlined in that section (~50 miles) and saw very considerable seepage losses. Reclamation estimated losses to be about 168,470 acre-feet per year in that section alone (USBR, 2018). The canal lining was completed in 1980 and considerable reduction in seepage losses have been observed. This reclaimed water is now held in storage reservoirs upstream and is better managed to serve the public.

One of the main issues associated with concrete lining is the required maintenance. Over time concrete will naturally deteriorate and concrete panels will need repairs or replacement. In order to do so, the water within a canal or reservoir has to be reduced to fully expose the damaged panel and must remain at that elevation while repairs are undertaken. Some structures cannot tolerate such outages; therefore, other methods, such as coffer dams, must be implemented to enable repairs. This can be very costly and can result in significant impacts to regular water management.

Geosynthetic liners

A popular method of mitigating seepage in large reservoirs and canals is the use of geosynthetic liners. Geosynthetic liners tend to be either High-Density Polyethylene (HDPE) or Polyvinyl Chloride (PVC) sheets that are welded together to provide a barrier to water losses. These liners can last for many years if they are properly maintained. The two main concerns for geosynthetic liners in water applications are degradation due to ultraviolet (UV) exposure and liner tears. Another issue of concern for water applications of geosynthetic liners is floating of the liner, which can occur when improperly installed or when hydrostatic conditions are not stable and the liner floats in the water. This is usually associated with poor construction, poor design, or poor operating procedures.

UV degradation occurs when a liner is exposed to direct sunlight. Commonly used geosynthetics tend to significantly degrade once exposed to UV light. Koerner et al. (2011) concluded that for a HDPE geomembrane, geosynthetic lifetime can significantly decrease if the liner is exposed. A non-exposed HDPE geomembrane at an in-service temperature is predicted to have a lifetime of about 446 years, while an exposed HDPE geomembrane in a dry and arid environment is currently estimated to have a lifetime of more than 36 years (tests ongoing). (Koerner et al., 2011).

The way to mitigate UV exposure is to install a soil cover over the liner as a barrier, both for UV and damage protection. This works well fordry facilities such as landfills, but is more of a concern for water facilities due to maintenance. As the facility operates normally, water tends to erode the soil cover and expose the liner to the environment. Therefore, maintenance has to be conducted to rebuild the liner cover. This has to be done by removing any material adjacent to the missing cover soil to properly fill and compact the area. This process requires operational changes that might not be possible or have significant impacts on water management.

The second concern for geosynthetic liners is liner tears. Geosynthetic liners are highly prone to punctures, tears, and overall physical damage. There are standard construction practices that help reduce the possibility of puncture and tear of the liner. However, the geosynthetic liners can still be damaged while already installed due to factors that have not been implemented into current practice.

Giroud et al. (1995) proposed strain concentration factors induced at seams and at QA/QC patches through theoretical methods. These strain concentrations occur at the seams as two geosynthetic sections that are not perfectly co-planar are stretched in tension. As they are stretched, a bending moment occurs at the seam. Giroud (2005) presented a series of plots that depict the strain concentration of different seam types. These strain concentration factors can further increase due to external loads such as seismic loads. EMCON (1994) concluded that the tears that occurred at the Chiquita Canyon Landfill during the 1994 Northridge Earthquake occurred along the QA/QC patch seams even though the liner system was designed to state-of-practice at the time.

Further work was completed to validate Giroud's strain concentration factors and seismic loading by researchers (Arab, 2011, Kavazanjian et al. 2013, Kavazanjian and Gutierrez (2017), Gutierrez, 2016, Wu, 2017). One of the most recent studies completed was by Kavazanjian et al. (2017) where strain concentrations were evaluated experimentally and shown to be present along seams and at levels possibly higher than the strain concentration previously determined by Giroud (2005).

Changes have to occur within design guidelines for geosynthetic liners for strain concentrations to be addressed. A tear in a liner could be as simple as placing a patch on the geomembrane or as serious as requiring a complete replacement of a section of a liner. Therefore, tears in liners could potentially be very costly and cause significant operational challenges.

Remove and Replace Soil

Remove and replace is a simple technique used in all types of geotechnical applications. It involves removing problem soils and replacing them with appropriate soil to meet design requirements. This method can be extremely costly or unfeasible in certain applications. For example, if there is a dam that was constructed on top of soil with a high hydraulic conductivity, it is unfeasible to remove and replace the soil. Therefore, this method is not typically used in large scale projects due to cost and is being replaced by more technical methods of soil improvement.

Grouting

Grouting is probably one of the most widely accepted methods of soil improvement and is widely used for seepage and internal erosion mitigation. Grouting covers a series of methods that introduce materials into the soil with pressure. The treated soil can have physical changes induced through grouting that range from waterproofing to strength increase. Grouting typically involves drilling a borehole into the problematic soil or rock and injecting the desired material. The injection material can be chemical grouts, low permeability soils, concrete, etc. Virtually any material can be injected that can produce a desired effect in the problematic soil.

The main disadvantage of grouting is knowing which method to use with your soil conditions (FHWA, 2017). Grouting technology is highly dependent on soil type. If grouting is used to reduce seepage under an embankment dam, special QA/QC criteria have to be analyzed to make sure grouting does not lead to potential blowout under the dam. Another disadvantage is cost can vary significantly and is hard to estimate prior to beginning of work. Since soil tends to be heterogeneous, certain zones of the soil media to be treated may require more or less grout than others thus resulting in unforeseen costs to a project.

Soil Mixing

The soil mixing method involves blending a binder with in-situ soil to improve properties that are desired at a particular site (FHWA, 2017). This method consists of a mixing apparatus that is introduced into the soil and mixes the soil with the binder that is being injected through the apparatus as it goes through the soil media. The binder material is typically a cementitious material that can reduce hydraulic conductivity and increase strength of the soil. There are two methods of soil mixing, a dry-method where the binder material is injected pneumatically and a wet method where the binder material is mixed with water and injected hydraulically. Soil mixing has become more acceptable within the United States and has been used to mitigate issues in embankments and dams (FHWA, 2013).

The potential disadvantages of using soil mixing methods are associated with limited familiarity with the method within the United States. Soil mixing requires specialized design, construction, specifications, and QA/QC practices (FHWA, 2017). It also can be extremely costly compared to other technologies due to the mobilization of heavy equipment. Soil mixing can also have issues in soils containing large boulders or debris within as these can impede with penetration of the mixing equipment (FHWA 2017).

Bio-Barriers

A new state-of-the-art approach to mitigation of seepage and internal erosion is the implementation of bio-barriers. Bio-barriers for soil improvement can be created through two different pathways: (1) bio-inspired processes which are abiotic and mimic natural processes and (2) bio-mediated process that stimulate native soil microorganisms. Bio-barriers for the purpose of seepage and erosion control aim for permeability reduction within an existing soil barrier or form mineral blockages along a seepage path. Many researchers have analyzed the implementation of bio-barriers of different types such as mineral clogging, particle cementation, biofilm production, etc. These methods show potential promise in achieving the desired effects for water facilities while being sustainable, cost-effective, and have little impact to regular operations of facilities.

Desaturation

Researchers, such as Fredlund et al. (1994), have been proposing methods to estimate hydraulic conductivity of soils throughout the years. Under both saturated and unsaturated conditions, water flow takes place in response to the effective potential gradient and in the direction of decreasing potential. However, unlike flow in saturated conditions, water flow in unsaturated conditions occurs in response to a potential gradient that exists in sub-atmospheric pressure conditions. The negative pressures (suction) that occur under these conditions are the result of the physical affinity of water to soil particle surfaces and capillary pores. The resulting tendency is for the water to be drawn from areas of higher potential to lower potential.

It is well understood that soil hydraulic conductivity in unsaturated conditions is a function of soil water content and the underlying driving factor of matric potential. Several empirical equations have been proposed to describe the complex interrelationship that exists between unsaturated hydraulic conductivity and the physical properties of soils e.g. Mualem, 1976; Van Genuchten, 1980.

Carsel & Parrish (1988) provided the data used to depict the relationship between unsaturated hydraulic conductivity, volumetric moisture, and suction head as seen in Figures 1 and 2. Figures 1 & 2 demonstrate the rapid decrease of hydraulic conductivity response as saturation decreases.

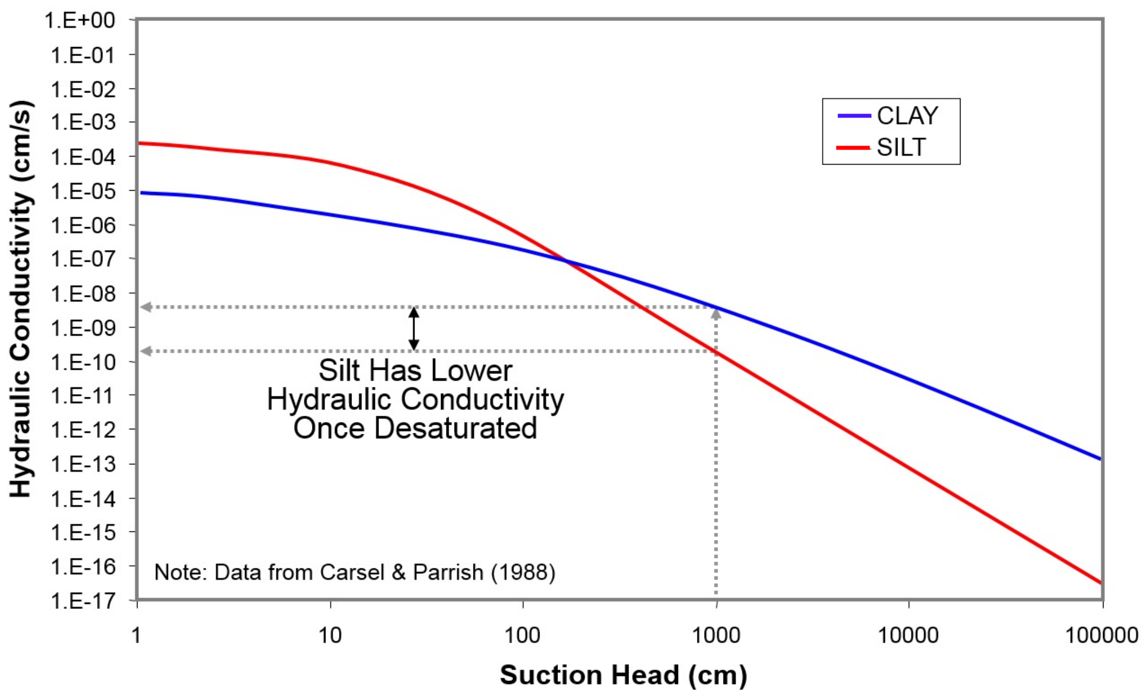

Figure 1. Typical unsaturated hydraulic conductivity response curves.

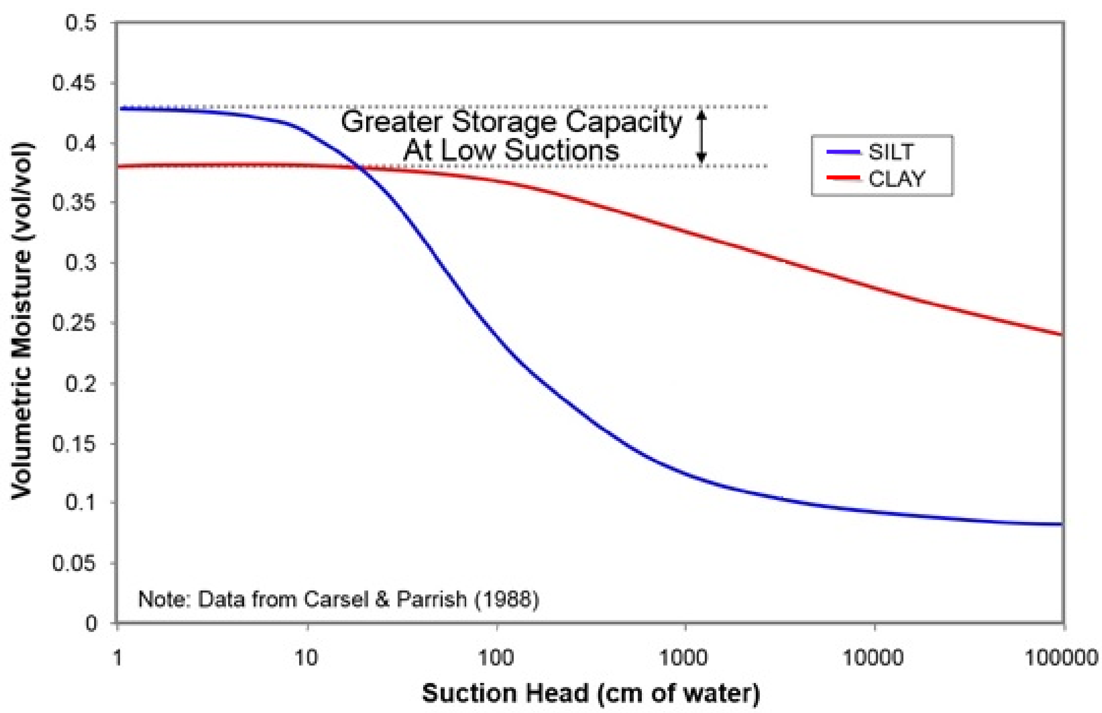

Figure 2. Typical soil moisture retention characteristic curves.

Researchers have been working on desaturation as a means to mitigate liquefaction in soils for years (Tsukamoto et al., 2002; Yang et al., 2004; Yegian et al., 2007). Researchers have demonstrated that naturally occurring methods of desaturation, such as microbial denitrification, can lead to a reduction in the degree of saturation by 5-20% (He et al., 2013). Denitrification, as defined by O'Donnell et al. (2017a), is a microbial metabolism in which nitrate (NO_3^-), the terminal electron receptor, is reduced to nitrogen gas; nitrogen gas (N_2) is a common, inert gas with very low water solubility that can displace soil pore water. Hamdan (2013) and O'Donnell et al. (2017a) went further by defining a process known as Microbially-Induced Desaturation and Precipitation (MIDP) as a two-stage biogeotechnical soil improvement method that uses native soil microbes for denitrification. In the first stage, denitrification produces N_2 gas to desaturate soil resulting in rapid improvement. The second stage is a slower mineral precipitation process that binds soil particles together with a calcium carbonate ($CaCO_3$) mineral. Equations 1 through 3 illustrate the biogeochemical process of MIDP.

$$2.6H^{+}{}_{(aq)} + 1.6NO_{3^{-}(aq)} + CH_3COO_{-(aq)} \rightarrow 0.8N_{2(g)} + 2CO_{2(g)} + 2.8H_2O \qquad (1)$$

$$CO_{2(g)} + H_2O \leftrightarrow HCO_{3^{-}(aq)} + H^{+}{}_{(aq)} \qquad (2)$$

$$Ca^{2+}{}_{(aq)} + HCO_{3^{-}(aq)} + OH_{-(aq)} = CaCO_{3(s)} + H_2O \qquad (3)$$

Equation 1 demonstrates how nitrate serves as an electron acceptor and is reduced to nitrogen gas. The nitrogen gas is a benign end-product that remains in solution throughout the process and therefore desaturates the soil. This in turn leads to a reduction in hydraulic conductivity and a reduction in seepage. However, Rebata-Landa and Santamarina (2012) have shown that the gas will not remain in the soil if it is composed of mostly sands with a limited amount of fines. Therefore, seepage mitigation through desaturation would only be a short-term process unless the local microbial community, specifically denitrifying organisms such as *Pseudomonas denitrificans*, are constantly stimulated. MIDP can still be applied as a viable solution for seepage mitigation as it is a two-stage process where the first step is desaturation as described above (also illustrated in Eq. 1) , followed by the second stage that results in soil cementation through carbonate mineral precipitation (illustrated in Eqs. 2 and 3).

Bio-Cementation

Bio-cementation has been a topic of great interest in recent years for the geotechnical community. Research has been ongoing on different ways to achieve cementation of soils including microbially-induced carbonate precipitation (MICP), enzyme-induced carbonate precipitation (EICP), and some bio-inspired methods such as abiotic applications of calcium chloride ($CaCl_2$) and sodium carbonate (Na_2CO_3). In all methods, including MIDP, cementation is achieved by the formation of $CaCO_3$. In all cases, there are three possible modes of soil improvement using bio-cementation: (1) soil cementation can occur at inter particle contacts and thereby bind particles together; (2) mineral precipitation can occur in the soil pore space and thereby increase soil density (i.e. pore-space "filling"); or (3) precipitation can occur on the soil particles and thereby “roughen” soil particle interactions which may result in greater strength and pore space reduction.

MICP can occur through different mechanisms such as denitrification (MIDP) mentioned in the previous section. However, many of the methods have undesirable side-effects that could be potentially harmful to the environment. Hamdan (2013) provided a table showing the different MICP mechanisms and undesirable side effects resulting from each. The focus of this study was on denitrification as it shows more promise as a means for soil improvement and seepage mitigation since it has no undesirable side-effects.

Table 1. Microbially induced carbonate precipitation mechanisms. (Hamdan, 2013)

Microbial Process	End Products	Undesirable Side-Effect
Bacterial Ureolysis	NH_3 (ammonia) NH_4^+ (ammonium)	Toxic gas Readily forms toxic salts
Sulfate Reduction	H_2S (hydrogen sulfide)	Toxic, Malodorous gas
Fermentation of Fatty Acids	CH_4 (methane)	Combustible gas
Denitrification	N_2 (nitrogen)	None

MIDP via microbial denitrification is a two-stage process as mentioned in the previous section. The generation of nitrogen gas continues as long as the native denitrifying bacteria found in soil are continuously stimulated. The second stage of the MIDP (cementation) typically begins within several weeks to months after stage-one. Mineral precipitation occurs when microbes alter the geochemistry of the pore water to favor precipitation of carbonate minerals (e.g. $CaCO_3$ as calcite), usually by raising pH, the carbonate alkalinity, or both in the presence of a suitable cation (O’Donnell et al., 2017b). As precipitation occurs, $CaCO_3$ forms throughout the soil mass. O’Donnell et al. (2017b) demonstrated that precipitation in MIDP columns tends to occur at the inter-particle contacts as the nitrogen gas bubbles “push” the precipitation to those areas. Soil particles also demonstrate particle roughening, or cementation occurring on soil surfaces which improves its dilatant behavior. Figure 3 shows scanning electron microscope (SEM) images of a) inter-particle cementation and b) particle roughening in continuous-flow column experiments conducted by O’Donnell et al. (2017b).

Most researchers have looked at MIDP as a means for soil improvement in terms of liquefaction mitigation. However, MIDP shows promise as a means of addressing seepage and internal erosion by desaturating, increasing particle roughness, and cementing particles that would otherwise be eroded away. Hamdan (2015) expressed concerns of MIDP not being applicable to pore sizes and soils smaller than fine sand. In order to treat and achieve cementation in finer sands and cohesionless silts researchers have studied EICP for soil improvement.

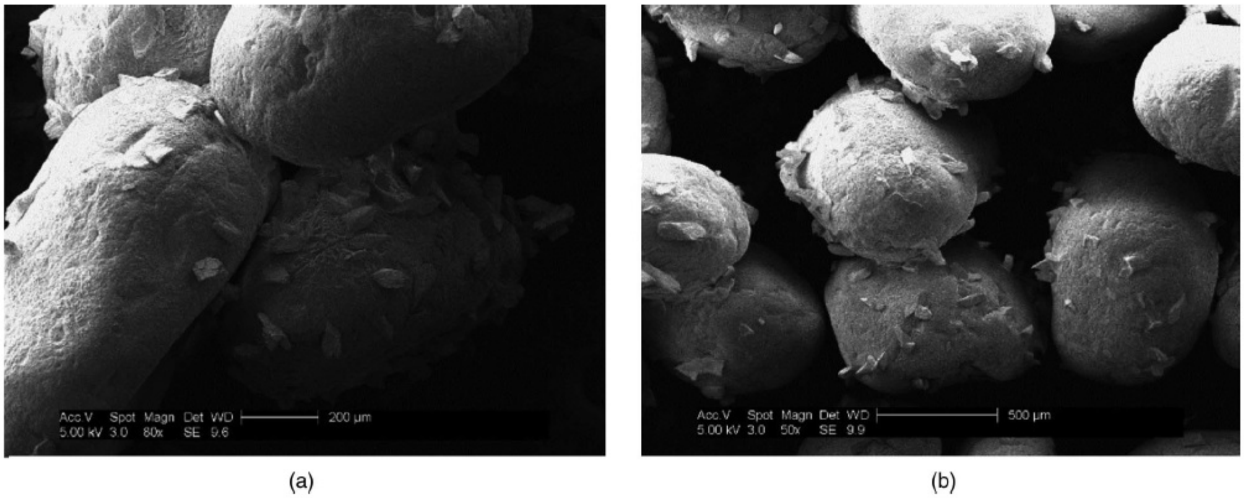

Figure 3. SEM images of treated soil showing a) inter-particle cementation; b) particle roughening.

Bio-Clogging

For the sake of brevity, this section will be limited to simply defining the phenomenon of bio-clogging and only briefly discussing its potential application for soil improvement primarily in the context of MIDP, MICP and EICP. Bio-clogging is a common phenomenon in nature and civil infrastructure. Although bio-clogging in civil infrastructure is usually undesirable, it is beneficial in situations where reduced porosity or low permeability is needed such as in earthen water conveyance structures. Bio-clogging of soils can be due to mineral precipitation, accumulation of biomass, and/or biogas production that leads to a reduction of porosity and hydraulic conductivity of the soil. There are several biotic and abiotic processes that lead to mineral precipitation and biogas production as discussed. Under the proper conditions, some biotic mechanism are capable of producing two or more of these processes for ground-improvement. MICP and MIDP are biotic processes that cause carbonate mineral precipitation for soil improvement as discussed above, but MIDP has the added advantage of biogas production (N_2). Under the proper conditions, both MIDP and MICP produce biomass that can result in porosity reduction and thereby provide an additional mode of ground improvement.

Alternatively, EICP is an abiotic process that causes carbonate mineral precipitation to bind soils and occurs without the accumulation of biomass. The very small size of the urease enzyme used in EICP and its abiotic pathway offers the advantage of deeper penetration into soils and extends the range of this mode of ground improvement to finer-grained soils than capable with MICP and MIDP. There are also other abiotic and biotic process that result various mineral precipitates including metal oxides that are a common occurrence in nature. Some of these process can be biologically induced by alterations in soil geochemistry using native soil microbes, and others can be facilitated more directly via abiotic methods including injections of specific combinations of inorganic agents.

Possible Test Areas

A number of possible test areas where identified within the Lower Colorado Region. These test areas where considered facilities that could have a significant impact to operations or economic and life loss if internal erosion lead to failure. One of the main areas considered for this application was Senator Wash, about 20 miles north of Yuma, Arizona. This embankment reservoir has severe seepage issues, has a current permanent reservoir restriction, and has to be continuously monitored for sand boil activity. Other than Senator Wash, most of the facilities are urban canal reaches that could have severe impacts. Appendix A summarizes Reclamation Urban Canal reaches with potential seepage issues within the LC Region.

Conclusions and Future Work

Seepage through earthen retention structures can represent a significant means of water loss and, if left unchecked, can lead to internal erosion and potential structural failure. Conventional approaches to mitigate seepage and internal erosion can be expensive, and possibly impracticable owing to environmental considerations and/or operational constraints. As an alternative, bio-mediated approaches to desaturation and cementation to reduce permeability and enhance structural integrity through pore space reduction (bio-barriers) have shown promise.

Naturally occurring methods of desaturation, such as microbial denitrification, through the production of N_2 to displace soil pore water have been show to provide for a reduction in the degree of saturation by 5-20%. In addition, both biotic and abiotic methods such as Microbially-Induced Desaturation and Precipitation (MIDP), Microbially-Induced Carbonate Precipitation (MICP), Enzyme-Induced Carbonate Precipitation (EICP), and some bio-inspired methods such as abiotic applications of calcium chloride ($CaCl_2$) and sodium carbonate (Na_2CO_3) can be used to induce carbonate calcium carbonate ($CaCO_3$) mineral precipitation for soil improvement. These methods show promise as attractive alternatives to mitigating seepage issues associated with earthen structures.

Future endeavors into the feasibility of using bio-barriers for seepage and internal erosion should focus on the applicability of the technology on local soils. The variability in microbial community and geochemical characteristics between different sites requires each test site to be analyzed. This analysis would determine if bio-barriers would be the correct method to use at each site. Therefore, the plan is to take soil samples from a number of areas of interest and conduct tests evaluating the compatibility of EICP, MIDP, or other methods to those soil characteristics. As research moves forward, more lab studies have to be to evaluate which methods of introduction would work best and from then on do large scale studies. These large scale “field” studies could be conducted at large research field stations, such as the one at Arizona State University’s Center for Bio-Mediated and Bio-Inspired Geotechnics.

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Appendix A – Inventory of Possible Test Sites in the Lower Colorado Region

Canal Name	Canal Reach ID	Lined	Lining Condition (TSC)	Canal Condition (YAO)	Canal Condition (TSC)	No. of Wet Inspection Points	Failure Likelihood (YAO)	Failure Likelihood (TSC)	Risk Level (YAO)	Risk Level (TSC)
All American Canal	6	Unlined	Fair	Good	Good	6	High-Very High	High-Very High	1C	1C
All American Canal	7	Unlined	Fair	Good	Fair	10	High-Very High	High-Very High	1A-3	1A-3
Coachella Canal	8	Lined	Fair	Good	Fair	3	Low-Moderate	Low-Moderate	1D	1D
Coachella Canal	9	Lined	Fair	Fair	Fair	27	Low-Moderate	Low-Moderate	1B	1B
Coachella Canal	10	Lined	Good	Fair	Good	3	Remote	Remote	1F	1F
Coachella Canal	11	Lined	Good	Good	Good	30	Remote	Remote	1F	1F
Coachella Canal	12	Lined	Fair	Good	Fair	5	Remote	Remote	1F	1F
Coachella Canal	13	Lined	Fair	Fair	Fair	13	Remote	Remote	1F	1F

Canal Name	Canal Reach ID	Lined	Lining Condition (TSC)	Canal Condition (YAO)	Canal Condition (TSC)	No. of Wet Inspection Points	Failure Likelihood (YAO)	Failure Likelihood (TSC)	Risk Level (YAO)	Risk Level (TSC)
Hayden-Rhodes Canal	14	Lined	Good	Good	Good	23	Low-Moderate	Low-Moderate	1B	1B
Hayden-Rhodes Canal	15	Lined	Fair	Good	Fair	15	Low-Moderate	Low-Moderate	1B	1B
Hayden-Rhodes Canal	16	Lined	Good	Good	Good	16	Low-Moderate	Low-Moderate	1B	1B
Hayden-Rhodes Canal	17	Lined	Good	Good	Good	18	Low-Moderate	Low-Moderate	1B	1B
Hayden-Rhodes Canal	18	Lined	Good	Good	Fair	24	Low-Moderate	Low-Moderate	1B	1B
A Canal	19	Lined	Good	Good	Good	14	Low-Moderate	Low-Moderate	1D	1D
Arizona Canal	20	Lined	Good	Good	Good	4	Low-Moderate	Low-Moderate	1B	1B
Arizona Canal	21	Lined	Poor	Good	Fair	10	Low-Moderate	Low-Moderate	1B	1B
Grand Canal	22	Lined	Poor	Good	Poor	13	Low-Moderate	High-Very High	1B	1A-4

Canal Name	Canal Reach ID	Lined	Lining Condition (TSC)	Canal Condition (YAO)	Canal Condition (TSC)	No. of Wet Inspection Points	Failure Likelihood (YAO)	Failure Likelihood (TSC)	Risk Level (YAO)	Risk Level (TSC)
Grand Canal	23	Lined	Poor	Good	Fair	10	Low-Moderate	Low-Moderate	1B	1B
South Canal	24	Lined	Fair	Fair	Fair	11	Low-Moderate	Low-Moderate	1D	1D
South Canal	25	Lined	Poor	Good	Fair	14	Low-Moderate	Low-Moderate	1B	1B
Tempe Canal	26	Lined	Poor	Good	Good	8	Low-Moderate	Low-Moderate	1B	1B
Western Canal	27	Lined	Good	Good	Good	11	Low-Moderate	Low-Moderate	1B	1B
Western Canal	28	Lined	Good	Good	Good	9	Low-Moderate	Low-Moderate	1D	1D
Western Canal	29	Lined	Good	Good	Fair	8	Low-Moderate	Low-Moderate	1D	1D
Western Canal	30	Lined	Fair	Good	Fair	6	Low-Moderate	Low-Moderate	1B	1B
East Main Canal	31	Unlined	Good	Good	Fair	12	High-Very High	High-Very High	1A-4	1A-4

Canal Name	Canal Reach ID	Lined	Lining Condition (TSC)	Canal Condition (YAO)	Canal Condition (TSC)	No. of Wet Inspection Points	Failure Likelihood (YAO)	Failure Likelihood (TSC)	Risk Level (YAO)	Risk Level (TSC)
East Main Canal	32	Unlined	Poor	Good	Fair	13	High-Very High	High-Very High	1A-4	1A-4
East Main Canal	33	Unlined	Fair	Good	Fair	8	High-Very High	High-Very High	1C	1C
East Main Canal	34	Unlined	Fair	Good	Fair	6	High-Very High	High-Very High	1C	1C
East Main Canal	35	Unlined	Fair	Good	Fair	11	High-Very High	High-Very High	1C	1C
East Main Canal	36	Unlined	Fair	Good	Poor	12	High-Very High	High-Very High	1C	1C
East Main Canal	37	Unlined	Poor	Good	Fair	18	High-Very High	High-Very High	1C	1C
East Main Canal	38	Lined	Fair	Good	Fair	1	Remote	Remote	1F	1F
West Main Canal	39	Unlined	Poor	Good	Poor	18	High-Very High	High-Very High	1A-4	1A-2
A Canal	40	Lined	Fair	Good	Good	11	Low-Moderate	Low-Moderate	1B	1B

Canal Name	Canal Reach ID	Lined	Lining Condition (TSC)	Canal Condition (YAO)	Canal Condition (TSC)	No. of Wet Inspection Points	Failure Likelihood (YAO)	Failure Likelihood (TSC)	Risk Level (YAO)	Risk Level (TSC)
A Canal	41	Lined	Fair	Good	Good	4	Low-Moderate	Low-Moderate	1B	1B
Grand Canal	42	Lined	Fair	Fair	Fair	23	Low-Moderate	Low-Moderate	1B	1B
Thacker Canal	44	Lined	Fair	Good	Fair	2	Remote	Remote	1F	1F
Thacker Canal	45	Lined	Good	Good	Fair	12	Low-Moderate	Low-Moderate	1D	1D
Thacker Canal	46	Lined	Fair	Good	Good	10	Low-Moderate	Low-Moderate	1B	1B
Thacker Canal	47	Lined	Good	Good	Fair	8	Low-Moderate	Low-Moderate	1B	1B
Thacker Canal	48	Unlined	Poor	Good	Fair	6	High-Very High	High-Very High	1A-4	1A-4
Thacker Canal	49	Unlined	Poor	Good	Fair	14	High-Very High	High-Very High	1A-4	1A-4
West Main Canal	52	Unlined	Fair	Good	Poor	13	High-Very High	High-Very High	1C	1C
West Main Canal	53	Unlined	Fair	Good	Poor	11	High-Very High	High-Very High	1C	1C

Canal Name	Canal Reach ID	Lined	Lining Condition (TSC)	Canal Condition (YAO)	Canal Condition (TSC)	No. of Wet Inspection Points	Failure Likelihood (YAO)	Failure Likelihood (TSC)	Risk Level (YAO)	Risk Level (TSC)
West Main Canal	54	Lined	Fair	Good	Fair	11	Remote	Remote	1F	1F
West Main Canal	55	Lined	Fair	Good	Fair	10	Low-Moderate	Low-Moderate	1B	1B
B Canal	268	Lined	Fair	Good	Good	23	Low-Moderate	Low-Moderate	1B	1B
B Canal	269	Lined	Fair	Good	Good	10	Low-Moderate	Low-Moderate	1D	1D
B Canal	270	Lined	Fair	Good	Good	11	Low-Moderate	Low-Moderate	1B	1B
B Canal	271	Lined	Fair	Good	Good	8	Low-Moderate	Low-Moderate	1D	1D
Cocopah Canal	272	Lined	Good	Good	Good	13	Low-Moderate	Low-Moderate	1D	1D
Cocopah Canal	273	Lined	Good	Good	Good	5	Low-Moderate	Low-Moderate	1D	1D
Cocopah Canal	274	Lined	Fair	Good	Good	6	Low-Moderate	Low-Moderate	1D	1D

Canal Name	Canal Reach ID	Lined	Lining Condition (TSC)	Canal Condition (YAO)	Canal Condition (TSC)	No. of Wet Inspection Points	Failure Likelihood (YAO)	Failure Likelihood (TSC)	Risk Level (YAO)	Risk Level (TSC)
Hayden-Rhodes Aqueduct Canal	275	Lined	Fair	Good	Good	23	Low-Moderate	Low-Moderate	1B	1B
Grand Canal/CrossCut	276	Lined	Fair	Good	Good	9	Low-Moderate	Low-Moderate	1B	1B
Arizona Canal	277	Lined	Fair	Fair	Fair	13	Low-Moderate	Low-Moderate	1B	1B
Western Canal	278	Lined	Fair	Good	Good	15	Low-Moderate	Low-Moderate	1B	1B
All American Canal	279	Unlined	Fair	Good	Poor	0	High-Very High	High-Very High	1C	1C