Design of Maintainable Drains for Earth Retaining Structures

Final Report and Design Guide
April 2017

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Skyline Steel LLC
Midwest Transportation Center
U.S. Department of Transportation
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Andrew Boeckmann and J. Erik Loehr

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Department of Civil and Environmental Engineering
University of Missouri-Columbia
E2509 Lafferre Hall
Columbia, MO 65211

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Midwest Transportation Center
2711 S. Loop Drive, Suite 4700
Ames, IA 50010-8664

Skyline Steel LLC
8 Woodhollow Road, Suite 102
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16. Abstract

Poor drainage is by far the most common cause of poor performance for earth retention systems. Poor performance includes burdensome serviceability problems that can progress to outright failure of the earth retention system if not addressed.

A common method for improving earth retaining wall drainage is to include weep holes, which relieve water pressure by creating a controlled seepage path through the retaining wall face. Maintainable drains are a more reliable means of promoting retaining wall drainage than traditional weep holes, which are likely to become clogged during the lifespan of the wall.

To evaluate performance of retaining walls with maintainable drains, the researchers constructed and tested two physical model retaining walls in the large-scale geotechnical modeling laboratory at the University of Missouri. The first wall retained a silty sand backfill, and the second wall retained a fine sand backfill. For each wall, a series of tests was conducted with varying drain type (maintainable and conventional weep), drain size (diameters of 2 in., 4 in., and 6 in.), and drain spacing. For each test, a constant height of water was impounded behind the wall backfill while measuring drain outflow and backfill pore pressure.

The research team created three-dimensional (3D) finite element models to evaluate the results of the physical models. The researchers created additional models to evaluate the effect of facial drainage features on a generic retaining wall.

The research team then developed design criteria for maintainable conical drains that penetrate the wall backfill, as well as for drains that do not penetrate the wall backfill, including conventional weep holes. The design criteria are general and do not address all situations, including situations when permittivity controls affect outflow, backfill is not compatible with the drain geotextile, or multiple rows of drains are used.

This report documents the project's research methodology, results, and interpretation. The interpretation culminated in the development of the team's *Design Guide for Maintainable Drains*, which is included as the Appendix to this report.

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DESIGN OF MAINTAINABLE DRAINS FOR EARTH RETAINING STRUCTURES

Final Report and Design Guide
April 2017

Principal Investigator
Andrew Boeckmann, Research Engineer
University of Missouri-Columbia

Co-Principal Investigator
J. Erik Loehr, Associate Professor
University of Missouri-Columbia

Research Assistants
Kyle Friedman, Eric Koenig, Ronald Roustio, and Sam Runge

Authors
Andrew Boeckmann and J. Erik Loehr

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A report from
Institute for Transportation
Iowa State University
2711 South Loop Drive, Suite 4700
Ames, IA 50010-8664
Phone: 515-294-8103 / Fax: 515-294-0467
www.intrans.iastate.edu

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INTRODUCTION

Poor drainage is by far the most common cause of poor performance for earth retention systems. Poor performance includes burdensome serviceability problems that can progress to outright failure of the retention system if not addressed. Figure 1 shows a catastrophic example of the consequences of inadequate earth retention wall drainage.

Figure 1. Failed earth retaining wall along I-70 in St. Charles, Missouri

A common method for improving retaining wall drainage is to include weep holes, which relieve water pressure by creating a controlled seepage path through the wall face. The Missouri Department of Transportation (MoDOT) typically includes weep holes in all cantilever retaining walls (Engineering Policy Guide 751.24.3). Weep holes can also be used as a stabilizing measure for distressed walls.

Traditional weep holes are beneficial in theory, but, in reality, their effect is often negated by clogging from any number of causes: improper backfill, vegetation, wildlife activity, or, as shown in Figure 2, human activity in the form of trash disposal.

Figure 2. Questionable weep holes in cantilever wall along Old Highway 63 in Columbia, Missouri

The stains shown in Figure 2 indicate previous operation, but clogging, loose debris, and lack of flow during wet periods call into question the current functionality of the weep holes. If the weep holes do not produce drainage, they provide no benefit.

Maintainable retaining wall drains (like the examples in Figure 3) are a more reliable means of promoting drainage than traditional weep holes.

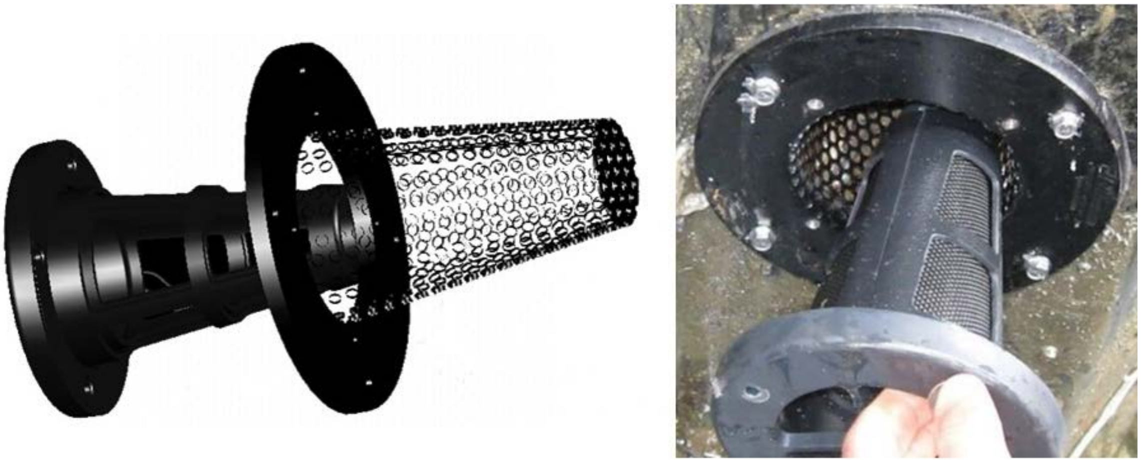

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Figure 3. Maintainable retaining wall drains consisting of two pieces: permanent housing that attaches to the retaining wall face and filter cartridge that inserts into the housing

The cartridge can be removed and re-inserted for cleaning or replacement of the filter fabric. Critical features of these maintainable drains are the ability to clean and/or replace the drain's filter fabric, thereby preventing clogging, as well as a means to readily install the drains in existing walls.

MoDOT has successfully used maintainable drains to halt movement of a retaining wall along I-44 at Berry Road in St. Louis, Missouri, but there are currently no MoDOT provisions related to the design or installation of maintainable drains. Development of design criteria for these types of drains would provide meaningful benefits, simultaneously improving retaining wall performance and reducing maintenance burdens. Provisions for the maintainable drains would also facilitate rapid deployment of the drains for emergency repairs.

To develop design criteria for the maintainable drains, the research team conducted a series of physical and numerical model tests. This report documents the project's research methodology, results, and interpretation. The interpretation culminated in the development of the team's *Design Guide for Maintainable Drains*, which is included as the Appendix to this report.

PHYSICAL MODELING, TESTING, AND RESULTS

The researchers constructed two model retaining walls measuring 8 ft wide by 4 ft tall in the large-scale geotechnical modeling laboratory at the University of Missouri. The first wall retained silty sand backfill, and the second wall retained fine sand backfill.

For each wall, the researchers performed a series of tests to evaluate performance of drainage features installed in the wall face. The drainage features varied in type (conventional weep holes and maintainable drains), size (diameters of 2, 4, and 6 in.), and spacing along the wall face. To test drain performance, a constant height of water was impounded behind the wall backfill while measuring outflow from the drains and pore pressures within the backfills.

This chapter documents the various components of the testing before describing the stages of testing and presenting results.

Maintainable Drains

Drainage features consisted of conical drains that were installed through the wall face and extended into the backfill. As shown previously in Figure 3, the drains consisted of two pieces: an outer cone permanently affixed to the wall face and an insert cone with a geotextile filter that attached to the outer cone. The insert piece could be removed for cleaning or for replacement of the geotextile filter (hence, “maintainable drain”). The geotextile used in the filters for testing was specified with an apparent opening size equivalent to a No. 30 sieve with a permittivity of 1.5 s^{-1}.

Model Container and Water Control

The model retaining walls were constructed inside the model container shown in Figure 4. The face of each model retaining wall was aligned with the front of the container, which is in the foreground of the photo in Figure 4.

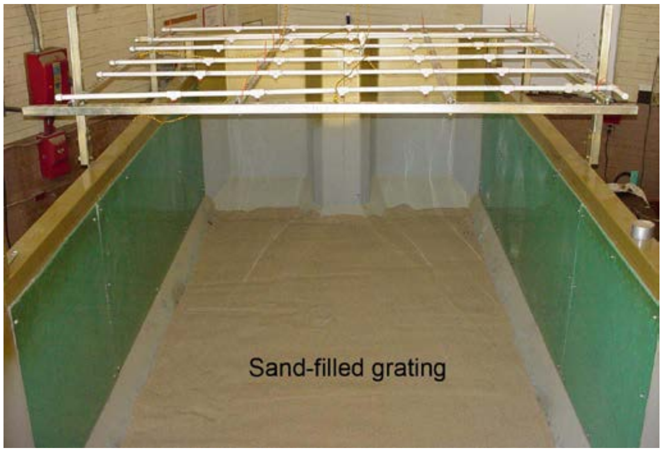
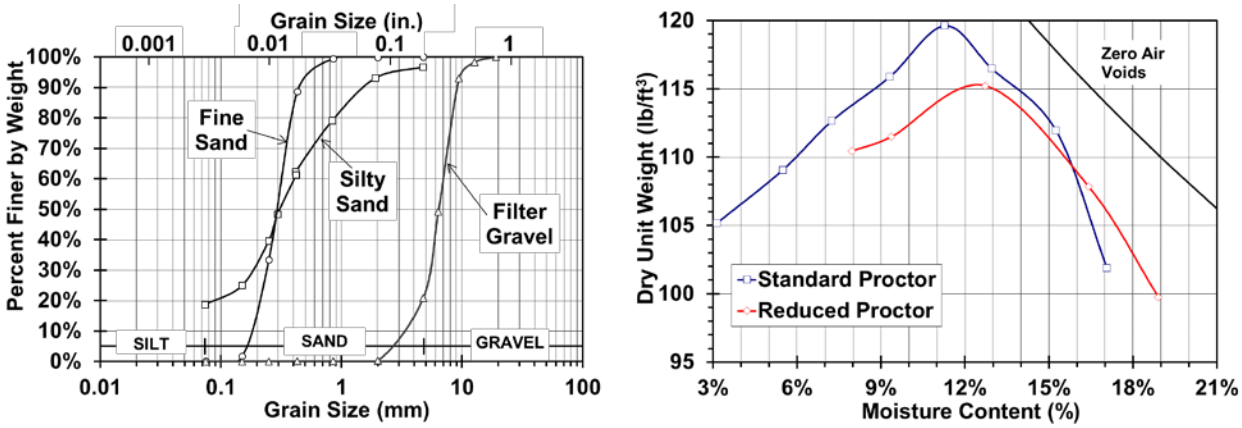


Figure 4. Model container in which retaining walls were built

The model container was 8 ft wide by 15 ft long with 4 ft tall sidewalls. A water control system consisting of 30 nozzles was fixed above the container. During testing, flow to the nozzles was controlled by a solenoid valve connected to a float switch inside the container to maintain a constant height of water. Each nozzle delivered 1.5 gal/h, and the data acquisition system recorded the time of operation during testing, so the total volume of water into the model container was approximately known.

Test Soil Characteristics

Two test soils were used for the retaining wall backfill. The first series of tests were performed on a wall with silty sand backfill. The second series of tests were performed on a wall with fine sand backfill. Both test sands had the same source material, but the fine sand was washed and screened to produce a more uniform gradation, as shown in the chart on the left in Figure 5. Standard and reduced Proctor compaction curves for the silty sand are shown in the chart on the right in Figure 5.



Reduced Proctor specimens were compacted with 10 blows per lift

Figure 5. Grain size distributions for test soils (left) and Proctor compaction curves for the silty sand (right)

To account for the method of compaction used during construction, a reduced Proctor test was performed to accompany the standard Proctor test. Both tests were performed according to ASTM Standard D698 (2012), but the reduced Proctor test specimens used 10 blows per lift instead of the specified 25. In addition, the hydraulic conductivity of compacted specimens was measured according to ASTM Standard D5856 (2015).

For reduced Proctor compacted specimens with water contents from 5 to 9 percent, the hydraulic conductivity was approximately 3x10^{-6} ft/s (1x10^{-4} cm/s). Hydraulic conductivity of the fine sand was measured with a constant head test (ASTM Standard D2434 2006) to be 2x10^{-3} ft/s (6x10^{-2} cm/s).

Instrumentation

Testing of the model retaining walls included instrumentation to measure outflow from the drains and pore pressures within the wall backfills. Outflow was measured with tipping-bucket style gages (see Figure 6).

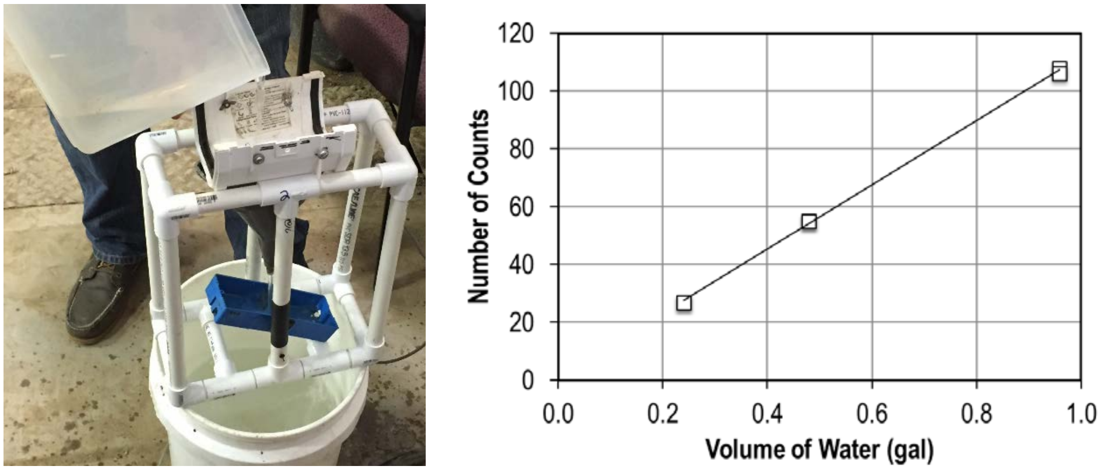


Figure 6. Calibration of tipping bucket devices used to measure outflow from model drains

A magnetic counter recorded the number of times the bucket tipped, which corresponded to a known volume of water according to the calibration shown on the right in Figure 6. During testing, flow rates interpreted from the tipping-bucket gages were verified by weighing the volume of seepage from the model during 10-minute intervals.

The flexible tube tensiometers shown in Figure 7 were used to measure pore pressures throughout the retaining wall backfill.

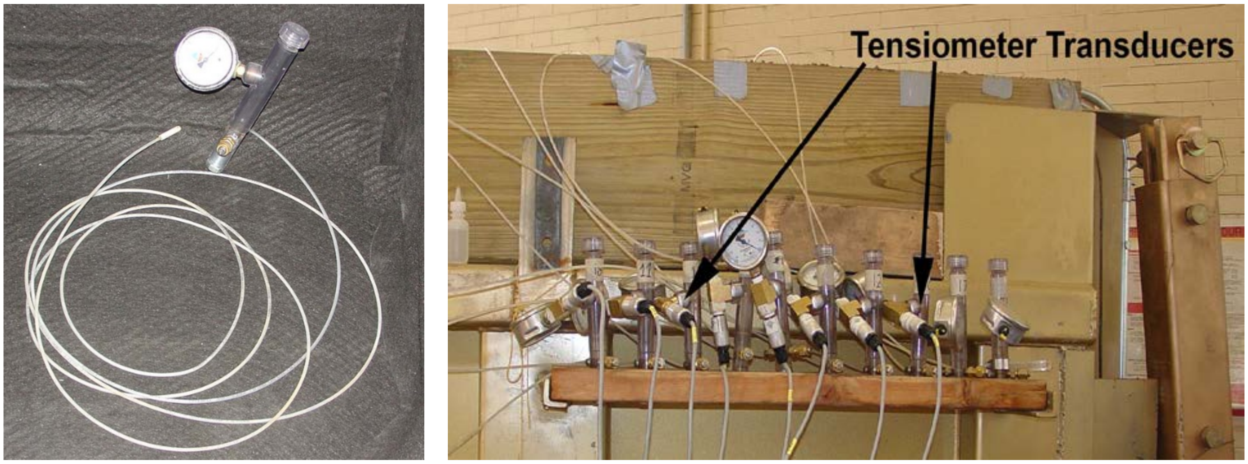
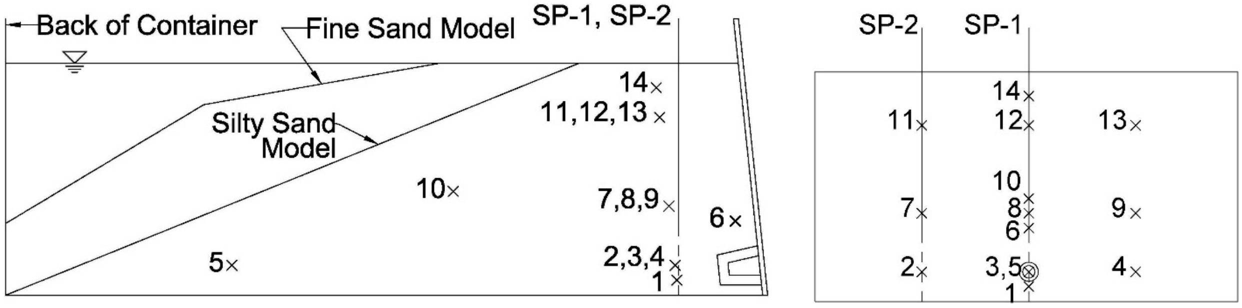


Figure 7. Flexible tube tensiometer before installation (left) and tensiometer reservoirs mounted on outside of model container (right)

The operating principle of the tensiometer is that unsaturated soil imposes a negative pressure (suction) on the saturated porous ceramic tip. The suction is transferred through the flexible line to a reservoir and pressure gage at the opposite end of the instrument. As shown in Figure 7, the tensiometer gages were mounted outside the container to allow positive pore water pressure to be measured in addition to suction. The tensiometers were equipped with both electronic pressure transducers and Bourdon tube gages to allow for visual inspection of pore pressures and to verify output from the voltage transducers. The locations of the 14 tensiometers used during testing are shown (marked by ×s) in Figure 8.



SP=standpipe piezometer and ×=tensiometer

Figure 8. Instrumentation locations: cross section view (left) and front view (right) of retaining wall

In addition, two standpipe (SP) piezometers were installed to measure the phreatic surface during testing. The PVC standpipes were installed full-depth and were located 2 ft behind the face of the retaining wall.

The bottom 1 ft increment of each standpipe was slotted so that water levels in the standpipes corresponded to pore pressures in the backfill approximately 1.5 ft behind the drain. A filter fabric covered the slots to prevent material from entering the pipes.

Construction of Model Retaining Wall

Photographs taken during construction of the model using the silty sand backfill are shown in Figures 9 and 10, and photographs of the final constructed wall and model are shown in Figure 11.

Figure 9. Inside of model container during construction

Figure 10. Back side of maintainable drain installed through center of retaining wall face during construction, with gravel placed around drain cone

Figure 11. Water impounded behind wall as viewed from above model container (top) and front view of model retaining wall (bottom)

For the first model, silty sand backfill was placed in approximately 9 in. thick lifts. The backfill was dry of optimum during placement, and several samples were taken from each lift to measure water content. Lifts were compacted using a 400 lb smooth drum roller. For the second model, fine sand backfill was placed without compaction using the bucket attachment of a small skid-steer loader.

As shown previously in the drawing on the left in Figure 8, the fine sand model was constructed with a greater total volume of backfill than the silty sand model. The volume was increased for the fine sand model in an effort to increase the seepage flow path distance and promote greater drawdown. The effect of backfill geometry is discussed in the Testing and Results section of this chapter and in the Numerical Modeling chapter.

The face of each retaining wall model consisted of wood boards measuring 1.5 in. thick by 11.25 in. tall, with the boards placed in advance of the backfill lifts. Wood boards were selected to facilitate simple laboratory construction of the wall face. In reality, the maintainable drains generally can be installed in any type of wall face capable of supporting a hole extending to the backfill (e.g., steel sheet pile walls, concrete cantilever walls).

Plastic sheeting was used to reduce the volume of water that would leak along the sides and bottom of the model container as well as the amount of seepage through the retaining wall face. Additionally, the inside of the bottom of the wall face was sealed with expansive polyurethane foam. During testing, some seepage was observed through the face of the model wall (e.g., Figure 11), but the rate of seepage was too small to be measured.

During construction of the silty sand model wall, one 4 in. diameter maintainable drain was installed in the center of the retaining wall face just above the bottom of the wall. The inside outer cone of the maintainable drain was surrounded with approximately 2 in. of gravel (as shown previously in Figure 10). During testing of the silty sand model wall, additional drains were installed closer to the sides of the model container, but these drains were inserted without gravel.

For the fine sand model wall, both maintainable and conventional weep holes were tested, and all drains were installed without gravel. Additional details about drain spacing and diameters during testing are presented in the next section.

Testing and Results

Testing of each retaining wall model included several stages, which are described in Table 1.

Drain type, diameter, and spacing varied between stages. Steady state flows from the drains are also listed in Table 1, along with the corresponding drawdown values observed in the standpipe piezometers. The drawdown values are the vertical distance between the elevation of the water surface ponded behind the backfill and the elevation of the water in the standpipes located 2 ft behind the face of the model walls.

Table 1. Physical model test stages

		Drain Information						Drawdown (in.)	
Model Backfill	Test Stage	Type	Diameter (in.)	Number	Effective Spacing (ft)	Gravel around Drain?	Total Drain Outflow Rate (gpm)	Center	Quarter point
Silty Sand	1	Maintainable	4	1	8	Yes	0.035	6.6	3.3
	2	Maintainable	2.5	1	8	Yes	0.032	4.8	3.3
	3	Maintainable	2.5	2	4	No	0.010	3.3	3.7
Fine Sand	1	Weep	2.5	1	8	No	0.30	7.1	6.9
	2	Maintainable	2.5	1	8	No	0.32	7.9	7.8
	3	Maintainable	4	1	8	No	1.00	11.7	11.6
	4	Maintainable	6	1	8	No	1.47	16.0	15.8
	5	Weep	6	1	8	No	0.67	9.0	8.9
	6	Weep	2.5	2	4	No	0.78*	12.3	12.8
	7	Maintainable	2.5	2	4	No	0.71*	11.5	12.0

*For test stages with two drains, the outflow value listed is the sum of flows from both drains

During Stage 1 for the silty sand backfill model, a single 4 in. maintainable drain was installed in the center of the retaining wall face. As shown previously in Figure 10, the outer cone of the 4 in. drain was surrounded by approximately 2 in. of gravel on the backside of the wall during construction. After testing the 4 in. center drain, a 2.5 in. maintainable drain was inserted into the drain's 4 in. outer cone. With this configuration, the center drain had the same size within the backfill as the 4 in. drain with gravel, but the face of the drain was equal to a 2.5 in. drain. During Stage 3 of the silty sand backfill test, the center drain was sealed and two 2.5 in. maintainable drains were installed. The drains were located at outer quarter points along the wall face to test a spacing that was effectively half of what was used during Stages 1 and 2.

Testing of the fine sand backfill model consisted of seven stages, which included testing of three conventional weep holes and four maintainable drains. Between each test stage, a submersible pump was inserted in a well approximately 12 ft behind the wall face to dewater the backfill and facilitate swapping of the drains without significant loss of backfill through the wall face.

Several noteworthy observations arose from the test results (see Table 1):

- Drain outflows from the fine sand model were one to two orders of magnitude greater than drain outflows from the silty sand model. Drawdown in the fine sand backfill model was also considerably greater than in the silty sand backfill model. Backfill material was not the only difference between the models; the fine sand backfill model had a greater volume of backfill (see previous Figure 8, which shows the longer flow path and therefore more head loss).

- For the silty sand model, the total drain outflow was nearly the same for Stages 1 and 2. This indicates that the permittivity of the 2.5 in. drain was not controlled during the second stage of testing. If the permittivity were controlled, a more significant reduction in outflow between Stages 1 and 2 would be expected. Stage 3 resulted in notably less outflow than from the first two stages, which was likely a result of the smaller drain size into the backfill, especially with the absence of gravel around the 2 in. drains.

- Test results of the fine sand model indicate that both drain outflow and drawdown within the backfill increased with drain size.

- Both weep and maintainable drains were tested in the fine sand model. The effect of drain type depended on drain size. For 2.5 in. diameter drains installed at the same effective spacing, the outflow and drawdown values were similar regardless of drain type. For 6 in. diameter drains, the outflow and drawdown were approximately twice as great for the maintainable drain as for the conventional weep hole. A likely explanation for the difference between drain types is that the conical maintainable drains have a greater surface area compared to planar weep holes, which promotes increased drainage. The surface area effect is muted for smaller diameter drains, not only because the difference in surface area is less, but also because most of the increased surface area is contained in the wall face opening as opposed to being in contact with the backfill soil.

NUMERICAL MODELING

The research team created three-dimensional (3D) finite element models to evaluate the results of the physical models. The researchers created additional models to evaluate the effect of facial drainage features on a generic retaining wall. They created the numerical models using RS^3 3D Finite Element Analysis for Rock and Soil (Version 1.021) from Rocscience Inc. Results are presented in the following sections.

Numerical Model of Physical Model Retaining Wall Test

The RS^3 numerical model created from the silty sand backfill test is shown in Figure 12 in two and three dimensions.

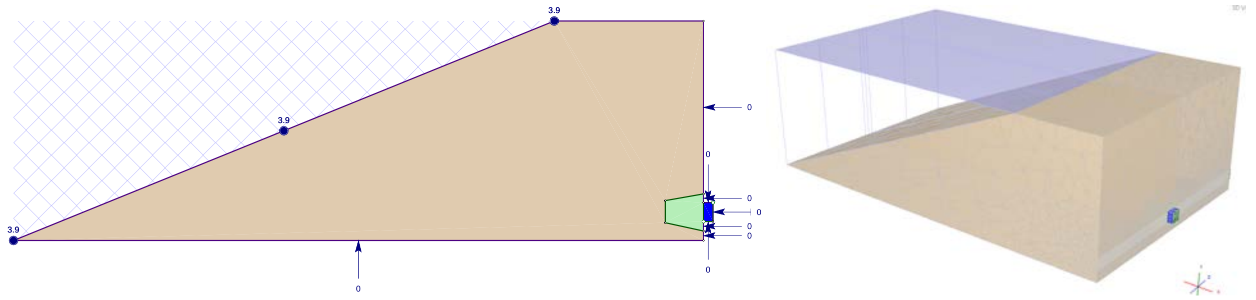


Figure 12. RS^3 numerical model for silty sand backfill test shown in 2D (left) and 3D (right)

The model includes three materials: silty sand backfill, gravel, and a material used to represent the drain. Hydraulic conductivity of the backfill was adjusted to calibrate the model, while the gravel material was used to model the gravel behind the drain (shown previously in Figure 10) as well as the empty space within the cone-shaped drain, to avoid including a void in the numerical model. The value of hydraulic conductivity used for gravel in the model was 3×10^{-2} ft/s (1 cm/s). The thickness and hydraulic conductivity of the region used to represent the drain were selected to equal the permittivity of the geotextile inside the drain (1.5 s^{-1}).

Boundary conditions are depicted in Figure 12. A total head boundary corresponding to the water level in the model container was applied to the exposed face of the backfill. No-flow boundaries were applied along every other boundary except for the face of the drain, where a seepage face was modeled. Seepage through the face of the retaining wall was therefore not included in the model; this is a reasonable approximation considering the small rate of seepage that was observed through the model’s wall face.

The 3D mesh is also shown in Figure 12 and consisted of multiple 10-node tetrahedrons.

The RS^3 model of the fine sand physical model was similar that for the silty sand model, but with slightly different backfill geometry to match the final constructed surface of the fine sand model, a different hydraulic conductivity value for the backfill, and drain inputs adjusted to match the configurations (shown previously in Table 1).

Calibration of the RS^3 models was achieved by adjusting the hydraulic conductivity of the backfill until the numerical model predicted values of drain outflow and drawdown that reasonably matched those listed previously in Table 1. Drawdown was primarily evaluated based on standpipe piezometer data, but tensiometer results were also considered. The evaluation of various trial models during calibration confirmed that drain outflow is sensitive to changes in backfill hydraulic conductivity. The same evaluations also revealed that drawdown is less sensitive to changes in backfill hydraulic conductivity and is affected more by changes in model geometry, with longer flow paths resulting in greater drawdown. This observation was the basis for increasing the volume of backfill used to construct the fine sand physical model to promote greater drawdown. Because drain outflow is sensitive to backfill hydraulic conductivity while drawdown is not, outflow measurements were more critical to the calibration of hydraulic conductivity values than piezometer or tensiometer measurements.

For the silty sand model, the calibrated hydraulic conductivity of the backfill was 2×10^{-5} ft/s (6×10^{-4} cm/s), which is approximately seven times greater than the value measured by ASTM Standard D698 (2012). For the fine sand model, the calibrated hydraulic conductivity of the backfill was 8×10^{-4} ft/s (2×10^{-2} cm/s), which is 2.5 times less than the value measured using ASTM Standard D2434 (2006). The differences between calibrated and laboratory hydraulic conductivity values are significant, but not unreasonable, considering the variability of hydraulic conductivity measurements for compacted soils.

Figure 13 shows interpreted values of the phreatic surface from tensiometers and piezometers as well as the phreatic surface predicted by the numerical model for Stage 1 of the silty sand backfill model and Stage 3 of the fine sand backfill model. Both stages included one 4 in. maintainable drain.

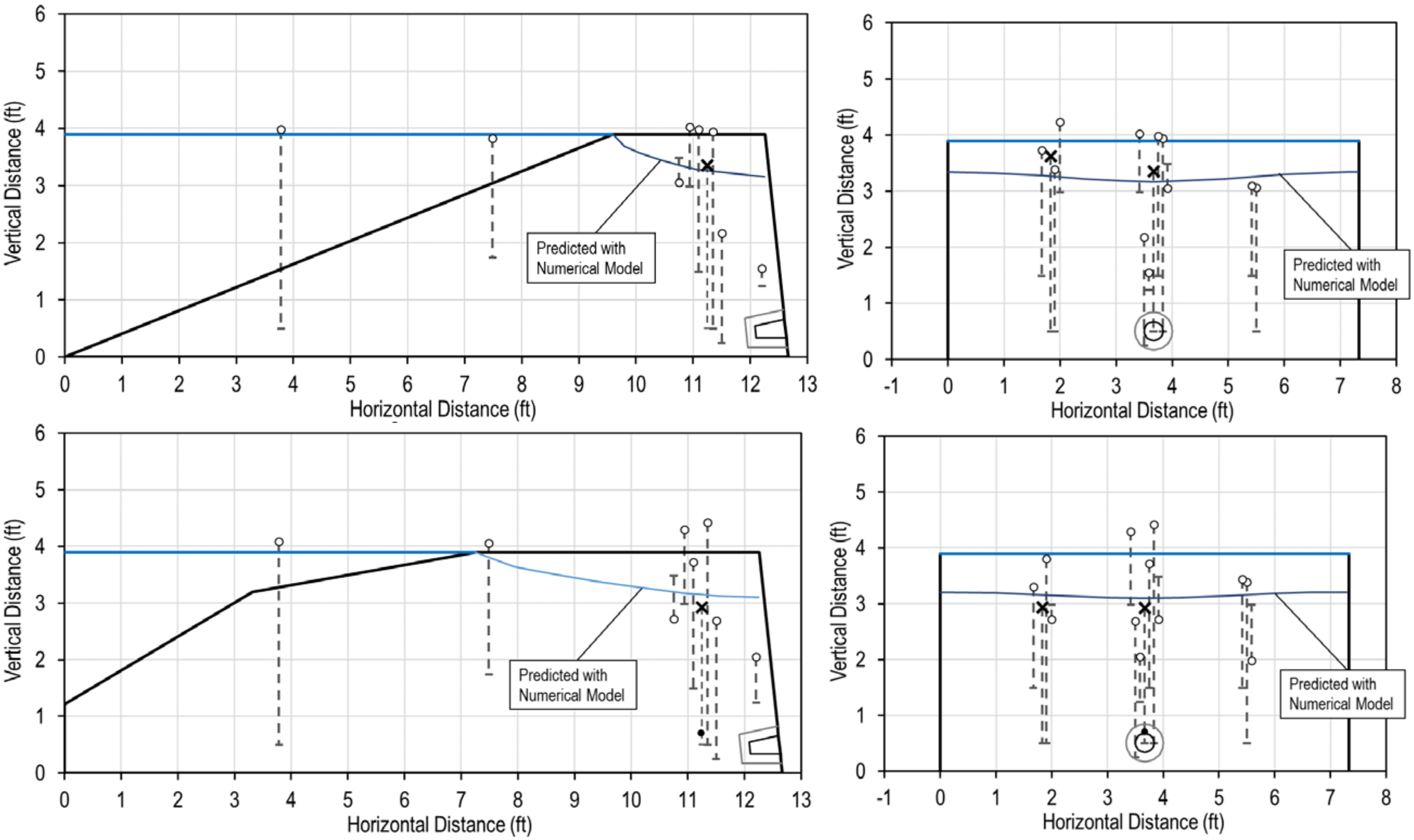


Figure 13. Phreatic surface observations from physical models and phreatic surface locations predicted by calibrated RS^3 models: cross section through center of silty sand backfill model during Stage 1 (top left), front view of silty sand backfill model during Stage 1 (top right), cross section through center of fine sand backfill model during Stage 3 (bottom left), and front view of fine sand backfill model during Stage 3 (bottom right)

The phreatic surfaces predicted by the numerical models are reasonably close to the locations observed in the physical models, and especially the piezometer observations. Locations interpreted from tensiometer pressures are more variable, but are generally consistent with the results from the numerical models. As discussed previously, the pore pressure regime predicted by the numerical models were strongly influenced by the geometry of the backfill and drain location and less by the backfill hydraulic conductivity.

Numerical Models for Full-Scale Retaining Walls

A separate RS^3 model was created to evaluate drainage feature design criteria for full-scale retaining walls. This numerical model was simple and included only three components: the drain, backfill, and a groundwater source behind the wall. The drain was modeled with gravel, similar to the model described previously. The backfill was modeled with a hydraulic conductivity of 3×10^{-5} ft/s (1×10^{-3} cm/s), which is similar to the fine sand used in the second physical model. Other values of hydraulic conductivity were evaluated but did not affect design criteria results significantly, as discussed in the next chapter.

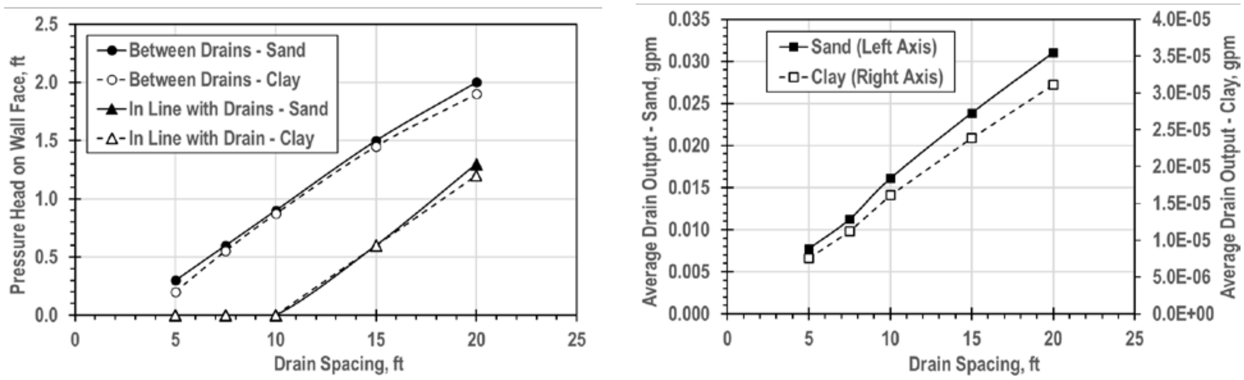
The location of the groundwater source (essentially the length of the finite element model) is an important parameter. If the location is relatively close to the face of the retaining wall, it greatly influences the drawdown resulting from the drains. A series of models with varying source distances were evaluated to determine an entry distance that appropriately balanced the impact on model results with the computational demand of the model. An entry distance of 1,000 ft was selected; the effect of this distance on model results was small, while greater entry distances have impractically high computational demand.

DESIGN CRITERIA

To develop design criteria, several variations of the model described previously were evaluated. Three drain sizes were considered: 2.5, 4, and 6 in. (in diameter). In addition, two drain types were considered: conical drains (such as the maintainable drains), which penetrate the backfill, and conventional weep holes that do not penetrate the backfill.

For each drain configuration, multiple heights of groundwater above the drain were considered. For each combination of drain configuration and groundwater height, the drain spacing was varied to determine the effect of spacing on the pressure head on the face of the retaining wall and on the flow from the drains.

Sample results are included in Figure 14.



Note: Drain output values are plotted on separate axes in the chart on the right. Drain outflow values from the clay model are 1,000 times less than values from the sand model.

Figure 14. Results of design evaluation analysis for 4 in. conical drains and groundwater 20 ft above drain showing pressure head on wall face versus drain spacing (left) and drain outflow versus drain spacing (right)

Figure 14 includes results for sandy backfill with a hydraulic conductivity of 3×10^{-5} ft/s (1×10^{-3} cm/s) as well as clayey backfill with a hydraulic conductivity of 3×10^{-8} ft/s (1×10^{-6} cm/s). Note that drain output values are plotted on separate axes in the chart on the right, and that values from the clay backfill model shown are 1,000 times less than those from the sand backfill model.

As shown in Figure 14, the pressure head on the face of the retaining wall increases linearly as drain spacing increases, with greater pressure experienced between the drains compared to the cross-sectional plane of the drains. With closer drain spacing, no pressure developed in the plane of the drain (i.e., spacing of 10 ft and below in the chart on the left in Figure 14).

The results of Figure 14 show drain outflow increasing linearly with spacing; that there is no reduction in flow indicates the permittivity of the drains did not control for any of the configurations considered. The effect of hydraulic conductivity on the pore pressures predicted by the model is negligible, as demonstrated in the results of Figure 14. The drain outflow predicted by the model is directly proportional to backfill hydraulic conductivity; the predicted drain outflow values from the model with sand backfill are 1,000 times greater than the corresponding values in the model with clay backfill. These observations regarding the effect of backfill material on pore pressures and flow are consistent with observations of the physical models.

Design criteria were developed by determining the spacing at which no pressure developed above the drain elevation on the face of the retaining wall (i.e., spacing of 10 ft and below in the graph on the left in Figure 14). From a stability perspective, this is a relatively conservative criterion since it typically corresponded to less than 2 ft of pressure on the face of the wall between the drains. However, the criterion is prudent for maintenance and general performance considerations.

More aggressive criteria could be developed based on other considerations such as external and global stability for design of individual retaining walls. Other considerations that would require project-level analyses include walls with more than one row of drains (to determine the required vertical and horizontal spacing) and walls with drains consisting of geotextiles having permittivity not equal to 1.5 s^{-1}. Lastly, the design criteria do not consider filter compatibility with backfill material, which would more adversely affect the conventional (non-maintainable) weep holes.

The proposed general design criteria for each drain are shown in Figure 15, with points showing values determined from the numerical model analyses and lines interpreted by the researchers.

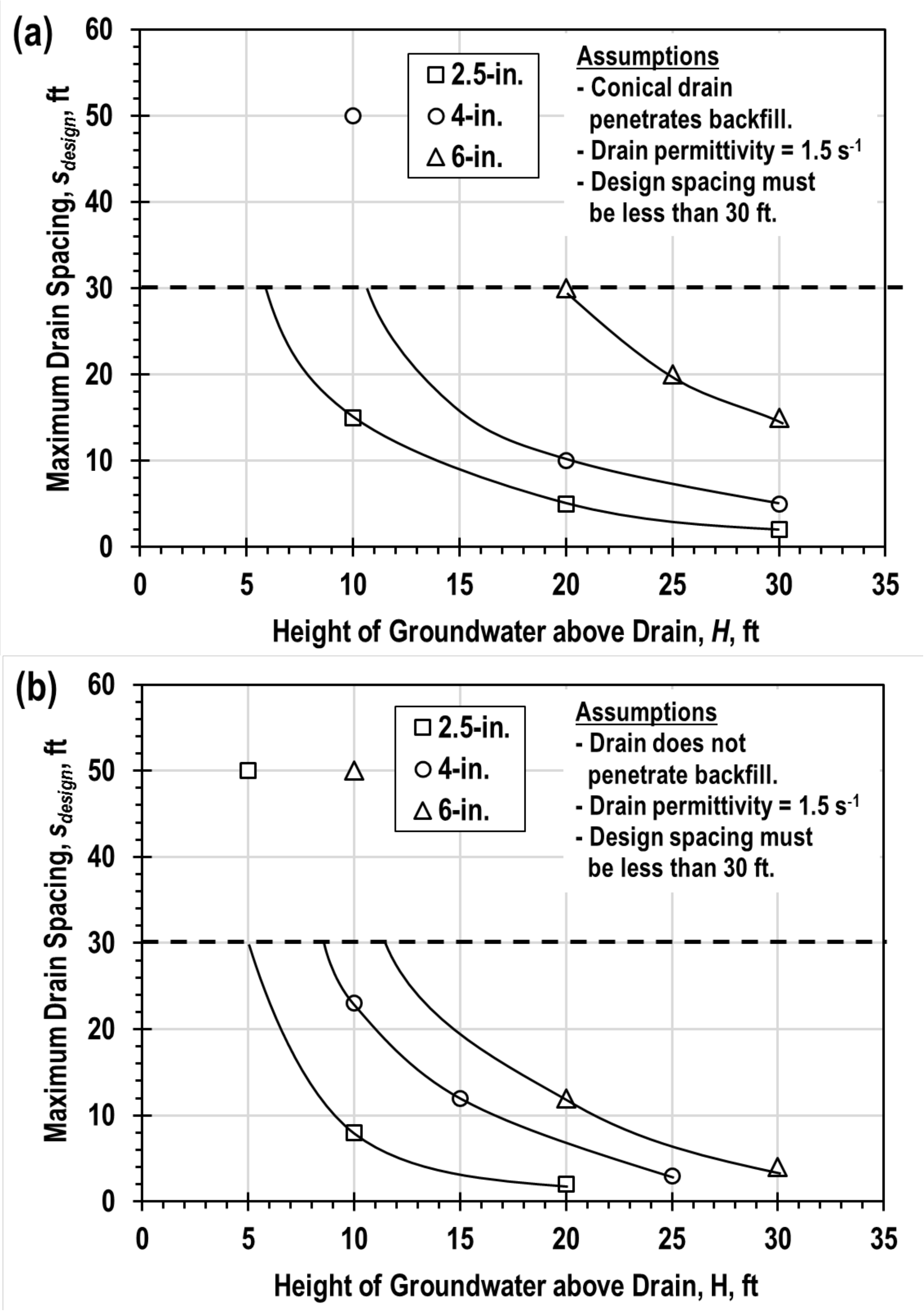


Figure 15. Design criteria results for conical drains that penetrate backfill (top) and drains that do not penetrate backfill (bottom)

Two sets of design criteria are presented in Figure 15: the top graph is for conical drains penetrating the backfill and the bottom graph is for drains that do not penetrate the backfill. The difference between the two sets of criteria is considerable, with backfill penetration by the drains corresponding to greater drawdown and therefore greater allowable spacing compared to drains that do not penetrate the wall backfill. The difference in the two sets of criteria is consistent with observations from the physical model tests.

Several other comments regarding the design criteria follow:

- The allowable spacing was capped at 30 ft to include a practical limit that accounted for local variations in groundwater conditions and any other potential considerations that could impact wall performance with greater spacing.

- The maintainable drains modeled for this study (see previous Figure 3) should only be designed according to the top graph in Figure 15 if the wall face thickness is thin enough to facilitate penetration of the backfill; otherwise (e.g., for thick concrete cantilever walls), the maintainable drains should be designed according to the bottom graph in Figure 15. All conventional weep holes should be designed as if they are drains that do not penetrate the backfill.

- The horizontal axis of Figure 15 was defined to allow designers some flexibility in vertical placement of the drains (rather than conservatively, but impractically, assuming the drain is at the base of the wall). As a result of this definition, the backfill material below the drain would be saturated and water pressure would be exerted on the wall face below the drain.

- For most values of groundwater height, several drain size-spacing combinations satisfy the design criterion, leaving designers the option to specify additional small drains or fewer large drains. Selecting the option of smaller drains at closer spacing is perhaps associated with greater reliability compared to larger drains at greater spacing, but the smaller drain design option is also likely associated with greater installation and maintenance costs. Designers should consider these impacts when selecting their design configuration.

SUMMARY AND CONCLUSIONS

The tests conducted on the physical and numerical models indicate that the inclusion of facial drainage features effectively reduces water pressure that develops on the retaining wall face.

The results from both the physical and numerical models indicate that backfill hydraulic conductivity controls the volume of seepage through the drains, but has less impact on drawdown within the backfill. Drawdown is controlled by geometric considerations, including the distance to the groundwater source, size of the drain, and penetration of the drain through the wall face into the backfill. Each of these effects were observed in the results from both the physical and numerical models. The effects are also reflected in the design criteria that the researchers developed using the numerical models.

The research team developed design criteria for maintainable conical drains that penetrate the wall backfill, as well as for drains that do not penetrate the wall backfill, including conventional weep holes. The latter set of criteria is associated with closer recommended drain spacing. The design criteria are general and do not address all situations, and notably situations when permittivity controls affect outflow, backfill is not compatible with the drain geotextile, or multiple rows of drains are included.

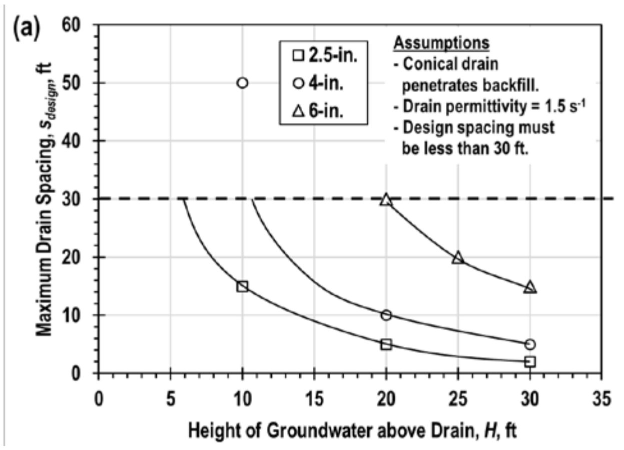
APPENDIX: *DESIGN GUIDE FOR MAINTAINABLE DRAINS*

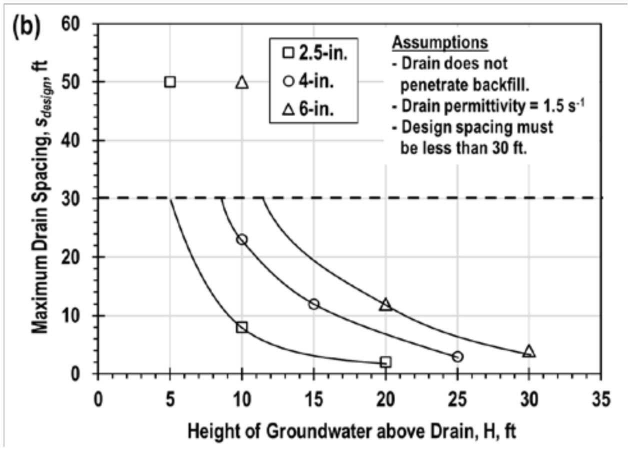
1. Gather required information.

a. Wall geometry:
  - Top of wall elevation, El_{top}
  - Bottom of wall elevation, El_{bottom}
  - Groundwater elevation, El_{gwt} (see notes in 2b below regarding selection)
  - Drain elevation, El_{drain}
  - Length of wall, l
  - Wall type
  - Wall face thickness

b. Minimum backfill information (more advanced information such as hydraulic conductivity or strength may be required for detailed analysis)
  - Soil classification (ASTM D2487-11 2011, AASHTO M 145 2012)
  - Gradation (ASTM C136-14 2014, AASHTO T 27 2014)

2. Select design drain spacing using the charts shown below.





"Spacing" is used throughout this guide to refer to the horizontal distance between successive drains, which are presumed to be installed in a single horizontal row along the length of the wall.

a. Will maintainable drain penetrate wall backfill? If yes, use chart (a); if no, use chart (b).

  Note:
  - Penetration of wall backfill results in a modest improvement in performance and is therefore associated with greater design spacing. It is conservative to assume no backfill penetration.
  - Consider the effect of wall thickness. For thick walls, it may be difficult or impossible to achieve backfill penetration.

b. Calculate the height of groundwater above drain, $H = El_{gwt} - El_{drain}$. The groundwater elevation is a critical input parameter and is often difficult to select:
   - Groundwater elevations fluctuate, and at some locations they fluctuate widely. The groundwater elevation encountered during subsurface investigation is not the permanent groundwater elevation.
   - Designers should select the highest groundwater elevation feasible during the life of the wall.
   - It is typically conservative to assume the groundwater will reach the top of the wall elevation. If the ground surface slopes up above the top of the wall, it may be prudent to use a groundwater elevation above the top of the wall.

c. Use design charts to identify the combinations of drain size and spacing that are allowable. The maximum design spacing for any size drain and any height of groundwater is 30 ft.
   Example: $H = 10$ ft, drain does not penetrate backfill. Allowable design options are 2.5 in. drains at a maximum spacing of 8 ft, 4 in. drains at a maximum spacing of 23 ft, and 6 in. drains at a maximum spacing of 30 ft.

d. For most values of groundwater height, several drain size-spacing combinations satisfy the design criterion, leaving designers the option to specify additional small drains or fewer large drains. Selecting the option of smaller drains at closer spacing is perhaps associated with greater reliability compared to larger drains at greater spacing, but the smaller drain design option is also likely associated with greater installation and maintenance costs.

3. **Check filter compatibility.**

a. Filter compatibility generally refers to the ability of a geotextile to satisfy competing demands for permeability and anti-clogging, which benefit from larger openings, with demands for soil retention, which benefit from smaller openings. For maintainable retaining wall drains, it is reasonable to give preference to the demands for permeability and anti-clogging given that the primary objective is drainage and the risk of significant ground loss through the drains is relatively small.

b. Several methods are available for evaluating filter compatibility. One common method is AASHTO M 288 (2015). The subsurface drainage criteria of AASHTO M 288 are summarized in the table below.

Backfill Material Fines Content (% Passing No. 200 Sieve)	Geotextile Requirements		
	Maximum Apparent Opening Size	Minimum Permittivity	Examples of Satisfactory Geotextile
<15	#40 (0.43 mm)	0.5 sec^{-1}	Mirafi FW 400, US Fabrics 230
15 – 50	#60 (0.25 mm)	0.2 sec^{-1}	
>50	#70 (0.22 mm)	0.1 sec^{-1}	Mirafi FW 700, US Fabrics 670

Examples of woven geotextiles satisfying the criteria are listed in the last column of the table, but many other suppliers offer geotextiles that satisfy the criteria.

c. If a filter fabric is specified that satisfies the permittivity criterion but not the apparent opening size criterion, the drain will likely provide adequate drainage, but the drain should be inspected regularly to ensure adequate backfill retention. If significant loss of backfill through the drain is observed, the drain fabric should be replaced with a fabric with smaller apparent opening size.

d. If a filter fabric that does not satisfy the minimum permittivity criterion is specified, the drain may not provide adequate drainage, and the charts for Step 2 may not be valid. A filter fabric with greater permittivity should be specified, or special analysis to determine the maximum drain spacing will be required.

4. **Develop final design details.**
   a. Determine the required number of drains, n_{drains}, by dividing the wall length, l, by the design spacing, s_{design}, and then rounding up the resulting quotient:

   $$n_{drains} = \left\lceil \frac{l}{s_{design}} \right\rceil$$

   b. Determine the construction spacing, $s_{construction}$, by dividing the length of the wall by the number of drains:

   $$s_{construction} = \frac{l}{n_{drains}}$$

   c. During construction, the drain locations should be centered along the wall such that the distance from each end of the wall to the nearest drain is half the construction spacing.

   d. For long walls with variable height, it may be advantageous to divide the wall into design segments and vary the drain details within each segment (e.g., use greater spacing near the ends of the wall, where the wall height is typically shorter, than near the middle of the wall).

Notes

a. The design charts were developed by determining the spacing at which no pressure develops above the drain elevation on the face of the retaining wall. For more information, see the Design Criteria chapter in the body of this report. The design charts do not address design of the overall wall system, including external stability (sliding, overturning, etc.) or global stability. Although improved drainage will result in improved external stability and perhaps improved global stability, external and global stability should be considered as part of the overall wall system design, separate from the procedure outlined in this guide.

b. The backfill material below the drain will be saturated and water pressure will be exerted on the wall face below the drain.

c. Periodic inspection of the drains should be incorporated into the maintenance plan for the retaining wall. Drain inspection should include removal of the inner piece of the drain to inspect the drain fabric and clean or replace as necessary.

d. This guide is being published as an appendix to Boeckmann, A. and J. E. Loehr. 2017. *Design of Maintainable Drains for Earth Retaining Structures*. Midwest Transportation Center and Institute for Transportation, Iowa State University, Ames, IA.