

Stress Analysis of Soils Adjacent to Selected Outlet Conduit Configurations for Small Embankment Dams

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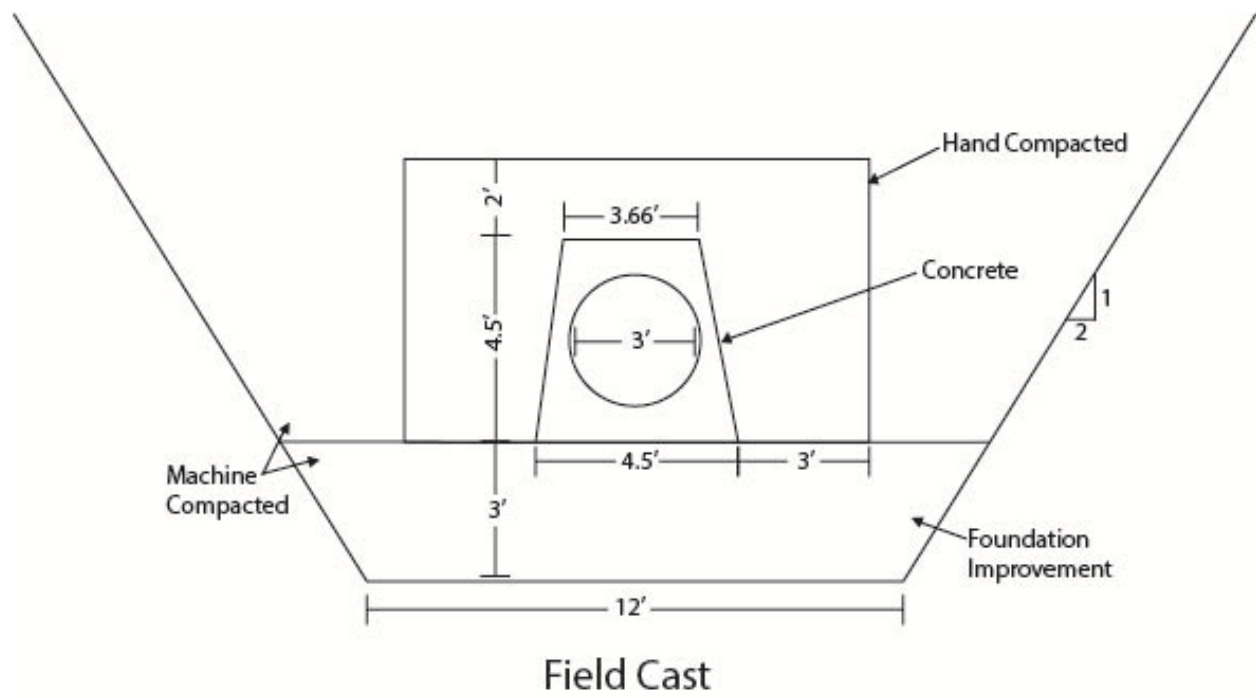
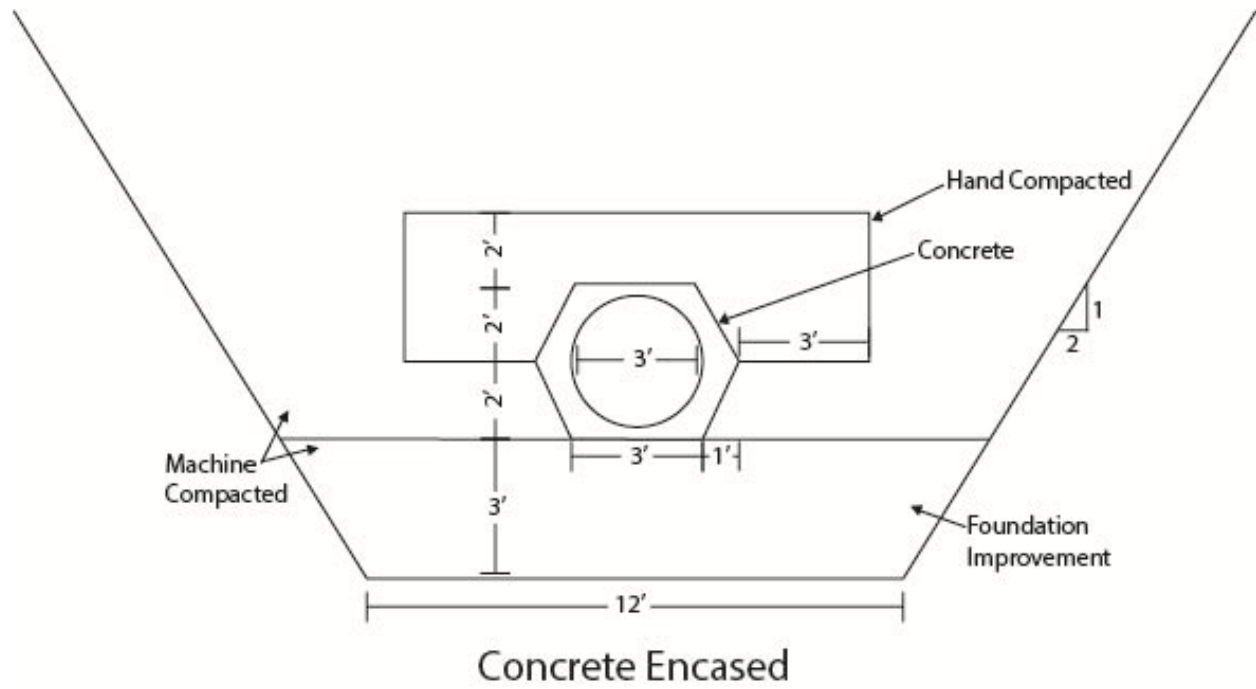
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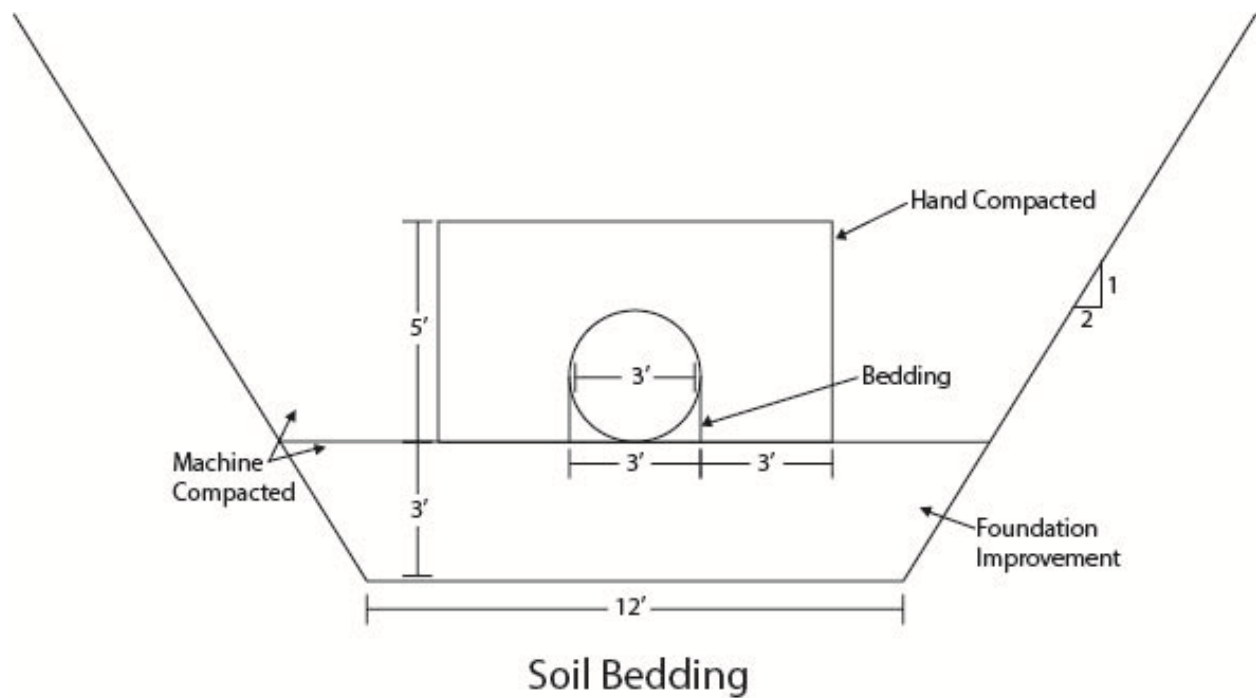
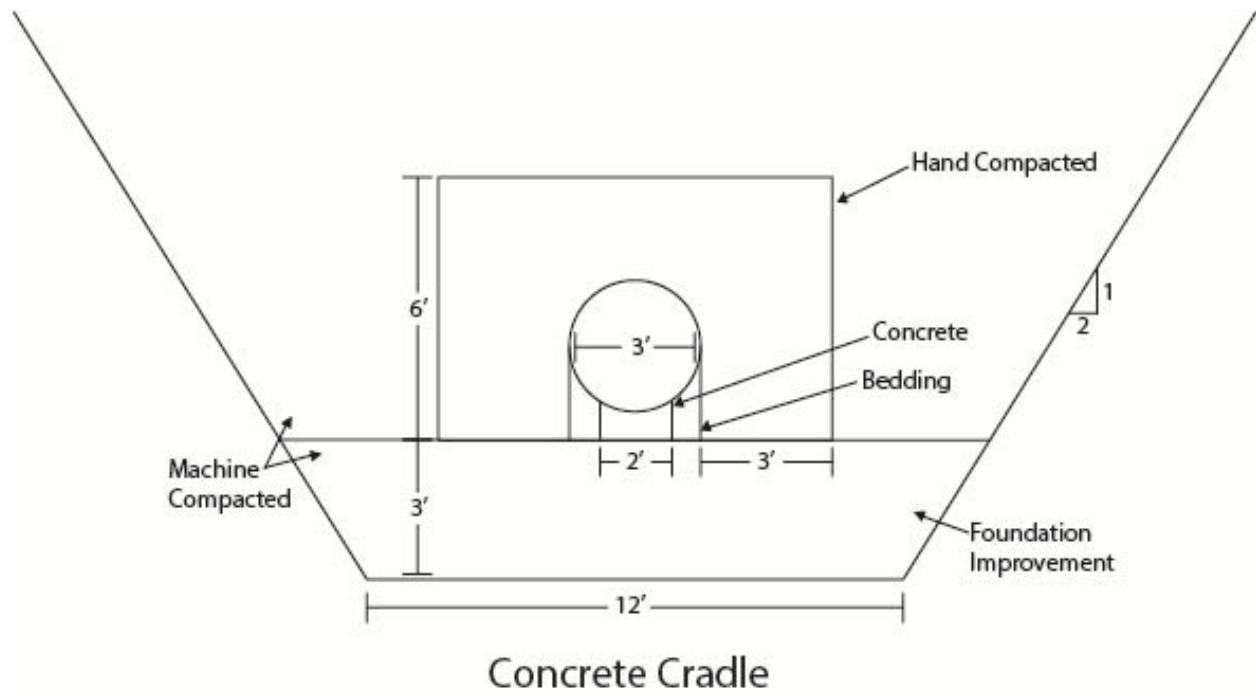
Introduction

Construction of relatively small (less than 50-feet high) earthen embankment dams have been commonplace throughout the United States over the last century. This includes over 11,400 Natural Resources Conservation Service (NRCS) Watershed Program dams, of which approximately 50 percent are over 50 years old. The Bureau of Land Management (BLM) has approximately 315 small embankment dams in Montana, with most of these over 40 years old. Many of these embankment dams have deteriorated and/or failed outlet conduits in need of replacement. This results in the need for a cost effective outlet replacement method for small dams.

The authors have utilized a trench and concrete encasement method on approximately 15 small embankment dams for the BLM in Montana over the past 12 years. The method was developed to facilitate rapid, low cost construction while maintaining positive principal stresses in the soil around the conduit circumference to minimize potential bridging effects and associated low-stress areas that would be susceptible to piping and hydraulic fracturing. Since these small dams are low-hazard, design budgets have been limited, precluding a formal stress analysis.

This study compares the above-described outlet configuration with three common outlet configurations. The four configurations are presented below and will be discussed in more detail on the subsequent pages:





Model Approach

In order to compare the behavior of the different outlet configurations with regards to soil stresses, a series of detailed stress analyses were completed using the SIGMA/W computer program. SIGMA/W is a finite-element software program used to evaluate stress and deformation of earth structures. The finite-element method is a numerical technique which divides complex problems into elements, which can each be solved in relation to each other. The elements, known as a mesh, can vary in both size and geometry. Generally, smaller elements are required in areas where soil parameters change significantly over a relatively small distance. For the analyses presented herein, a combination of quadrilateral and triangular elements ranging in size from one to five feet were utilized. The element sizes were chosen based on material boundaries and geometries of differing soil regions. Boundary conditions were assigned to elements based on known and assumed boundary conditions and included edge and pore pressure boundary conditions.

Based on the assumed typical site conditions, a coupled stress/pore water pressure analysis was selected, which solves both the stress-deformation and seepage dissipation equations simultaneously. This approach allowed for the evaluation of both immediate (elastic) settlement and long term consolidation settlement and stresses associated with each. Well compacted materials and materials located above the phreatic surface were assumed to behave linear-elastic, in which stress is directly proportional to strains. Soils susceptible to consolidation, i.e. weak foundation soils and hand compacted soils located below the phreatic surface, were assumed to behave as soft clay which allows the model to account for both elastic-plastic and consolidation behavior. Hydraulic conductivity and volumetric water content functions were applied to account for soil behavior below the phreatic surface.

The models utilized a 2-dimensional geometry that was based on the selected typical embankment profile. The models utilized time steps in which initial steps calculated existing in-situ stresses, stresses following excavation, and stresses associated with backfill placement. Stresses were modeled for a period of one year following completion of backfill placement at which time a stress redistribution model was ran to account for any potential over-stressing of soil elements. All results presented herein represent conditions at the end of the 1-year period.

Soil Parameters

As the purpose of this study was to compare outlet configurations, it was important to keep other variables such as soils types consistent. For this reason, it has been assumed that the typical embankment cross-section is comprised of a lean to fat clay with small percentages of sand. This is consistent with conditions at the small dams where the encasement configuration has been used in northern Montana and is typical of many small embankment dams.

Soil parameters were based on laboratory results from these dams and typical published values (NAVFAC, 1986). The parameters are representative of typical CL/CH soils often used in embankment dams found in northern Montana. Soil zones that were assumed to exhibit consolidation behavior were assigned typical parameters for compression indices, swell indices, and over consolidation ratios (OCR).

These soil parameters allowed for the ability to run coupled stress-pore pressure analyses to consider consolidation-related soil movement and accompanying stress changes.

The following describe each of the soil zones included in the model:

Embankment. The embankment soil zone represents the soil utilized to originally construct the dam that is not disturbed by the outlet replacement. It has been assumed that this material has been in-place for the life of the dam and has reached a state of equilibrium. The portion of the embankment above the phreatic surface is assumed to be drained, while the portion below the phreatic surface may undergo pore water pressure changes caused by unloading and loading during outlet works replacement.

Machine Compacted Backfill. The machine compacted soil zone consists of backfill material placed during outlet works replacement in areas accessible to modern heavy construction equipment producing high densities. Like the embankment, it has been assumed this material is drained above the phreatic surface and may experience pore water pressure changes below the phreatic surface.

Hand Compacted Backfill. The hand compacted soil zone is backfill material placed around the conduit as part of the outlet works replacement. This material is present in areas not accessible by heavy construction equipment and is compacted with hand operated equipment. For purposes of this study, this zone extends three feet on each side of the conduit and two feet over the conduit. Due to the nature of placement, it is assumed this material is placed at a lower density than the machine compacted embankment resulting in lower strength properties. This material is assumed to be drained above the phreatic surface and may experience pore water pressure changes below the phreatic surface.

Bedding. The bedding soil zone consists of material placed under the haunches of the conduit in the configurations that require compaction of soil into the haunch area. Due to the difficulty in compacting this area, it is assumed to have a lower density than other zones. Being located below the phreatic surface, it is assumed that this material may experience pore water pressure changes and undergo consolidation-related settlement.

Compressible Foundation. The compressible foundation soil zone consists of the upper foundation soils that exist beneath the embankment. This zone was assumed to be over-consolidated, but compressible to a degree and may experience pore water pressure changes. The compressible zone was assumed to be 10 feet in thickness.

Incompressible Foundation. The incompressible foundation soil zone consists of the lower foundation soils and is assumed to be incompressible. These soils may experience changes in pore water pressure, however relatively high strengths limit soil movement.

Foundation Improvement. The foundation improvement soil zone consists of material used to improve the compressible foundation soils immediately beneath the conduit. The improvement would consist of

over-excavation of the subgrade and replacement with well-compacted fill under the same controlled conditions as the machine compacted backfill.

The following table summarizes soils parameters and designations utilized in the analyses. All unit weights have been based on a maximum dry unit weight of 100 pcf.

Table 1 - Settlement Parameters							
Parameter ¹	Materials						
	Embankment	Machine Compacted Backfill	Hand Compacted Backfill	Bedding	Compressible Foundation	Incompressible Foundation	Foundation Improvement
Material Category	Effective Stress Drained/Effective Stress w/ PWP Change	Effective Stress w/ PWP Change/Effective Stress Drained	Effective Stress w/ PWP Change/Effective Stress Drained	Effective Stress w/ PWP Change	Effective Stress w/ PWP Change	Effective Stress w/ PWP Change	Effective Stress w/ PWP Change
Material Model	Linear Elastic	Linear Elastic	Soft Clay/Linear Elastic	Soft Clay	Soft Clay	Linear Elastic	Linear Elastic
E, psf	750,000 – moist 500,000 - sat	1,000,000 – moist 750,000 - sat	500,000	--	--	3,000,000	1,000,000
Unit Weight, pcf	115 – moist 125 – sat	120 – moist 130-sat	110 – moist 120 – sat	120 - sat	125 – sat	130 – sat	130 – sat
v	0.30	0.30	0.30	0.40	0.30	0.30	0.30
Saturated WC	30%	30%	30%	40%	30%	25%	30%
Moist WC	20%	20%	20%	20%	20%	20%	20%
k, ft/day	3e-4	3e-4	3e-3	1.0	3e-4	3e-4	3e-4
Residual WC	10%	10%	10%	10%	10%	10%	10%
OCR	--	--	1.0	0.75	1.5	--	--
λ	--	--	0.065	0.130	0.065	--	--
Cc	--	--	0.15	0.30	0.15	--	--
K	--	--	0.0065	0.013	0.0065	--	--
Cr	--	--	0.015	0.03	0.015	--	--
e ₀	--	--	0.70	0.80	0.65	--	--
ϕ'	--	--	0°	0°	0°	--	--

¹E = modulus of elasticity, v = Poisson's Ratio, WC = water content, k = hydraulic conductivity, OCR = Over-consolidation Ratio, $\lambda = Cc/2.303$, Cc = Compression Index, K = Cr/2.303, Cr = Swell Index, e₀ = initial void ratio, ϕ' – effective friction angle

Assumptions

In order to model the outlet configurations, certain assumptions were made. These assumptions prevented modeling problems such as convergence and eliminated other variables that could influence results, while still allowing for the ability to compare the different outlet configurations. Assumptions included:

- Soil nodes located at the extents of the model are fixed and do not undergo movement.
- Soils that have undergone high levels of compactive effort such as the existing embankment, compacted backfill, or incompressible foundation soils were assumed to behave linear-elastic with no consolidation behavior.
- The phreatic surface within embankment dams is highly dependent upon several variables including pool elevation, soil hydraulic conductivity, placement techniques, and the presence of internal drainage. In order to eliminate these variables, it has been assumed the phreatic surface corresponds with the top of the conduit prior to replacement activities.
- It has been assumed that the foundation improvement occurs as part of the conduit replacement.
- In order to make reasonable allowances for construction equipment, a minimum excavation width of 12 feet has been assumed.
- In order to analyze the potential low and high stress zones, an embankment height of 50 feet above the conduit has been utilized.
- Based on typical construction conditions an excavation slope of 2 (horizontal) : 1 (vertical) was selected.
- It was assumed conduit placement would occur in steps and backfill placement would occur over a period of 15 days.
- It was assumed the conduit is rigid and does not undergo deflection other than due to settlement of the underlying soil.
- A 36-inch diameter circular conduit has been utilized.
- The relationship between consolidation and swell indices is a factor of 10.

It should be noted the above assumptions were employed in order to compare the outlet configurations. Variables such as foundation improvement, excavation width, embankment height, and excavation slope were compared as part of a subsequent sensitivity analysis.

Table 2 and Figure1 summarize model dimensions that were held constant for the comparisons.

Component	Dimension
Embankment Height above conduit	50 ft
Conduit Diameter	36 inches
Excavation Slope	2 H: 1 V
Subgrade Improvement Depth	36 inches
Bottom Width	12 ft

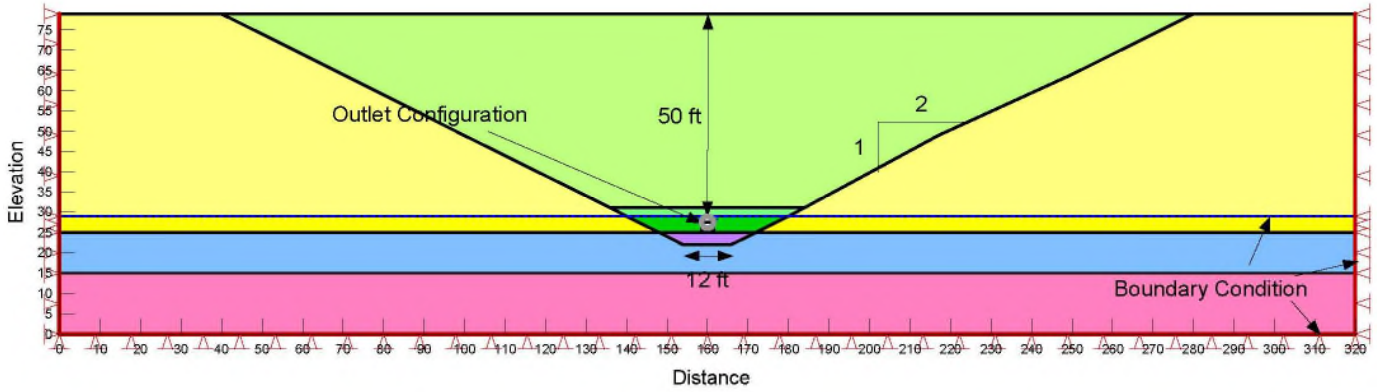


Figure 1 - Overall Model Geometry

Outlet Configurations

Four outlet configurations were analyzed as part of this study. The following sections describe each configuration and present a schematic associated with each configuration.

Soil Bedding Configuration

The soil bedding configuration shown below details the zones selected to represent typical trench conditions. Potential concerns regarding this configuration include low stresses that may be caused by the arching effect of the compacted soils above the pipe and the less dense compacted soils adjacent to and below the haunches of the pipe. The soil below the haunches will have relatively low compaction due to the limited access for placement/hand compaction.

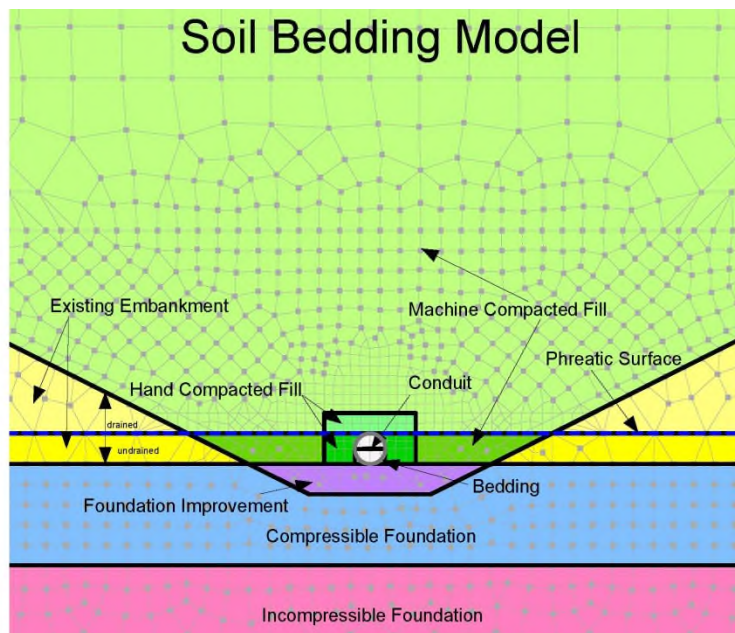


Figure 2 - Soil Bedding Configuration

Field Cast Conduit Configuration

The field cast conduit configuration shown below represents anticipated zones which are typically constructed in the field. This method can be very costly and time consuming to construct due to its cast-in-place nature, however, it is considered by many to be the best configuration to eliminate low-stress areas adjacent to the conduit. Areas immediately adjacent to the concrete may be problematic due the arching effect of the hand compacted clay soils causing areas of lower stress. Using rubber-tired equipment to improve compaction of the soil adjacent to the conduit is recommended.

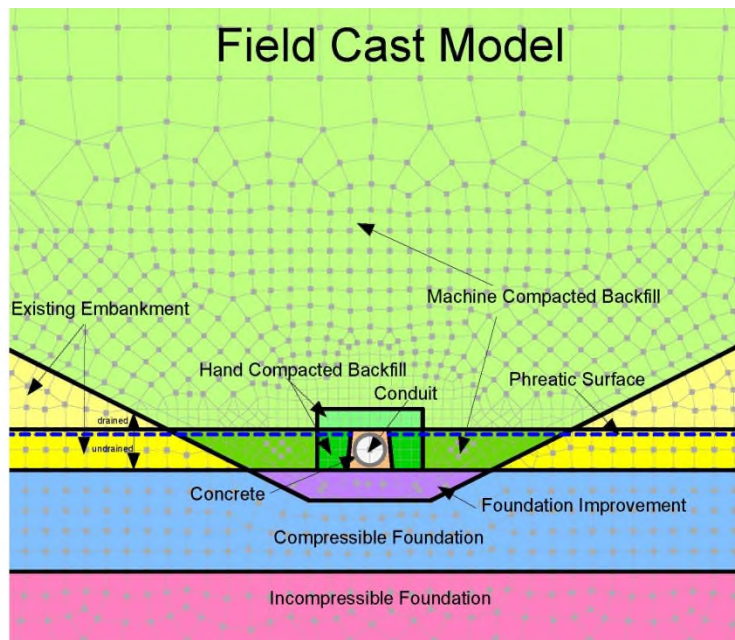


Figure 3 - Field Cast Configuration

Concrete Cradle Configuration

The concrete cradle configuration uses concrete bedding directly under the conduit limited to a width of 2/3 of the pipe diameter. Areas of concern with this configuration would be directly adjacent to the concrete cradle where poor soil compaction is likely due to the limited access.

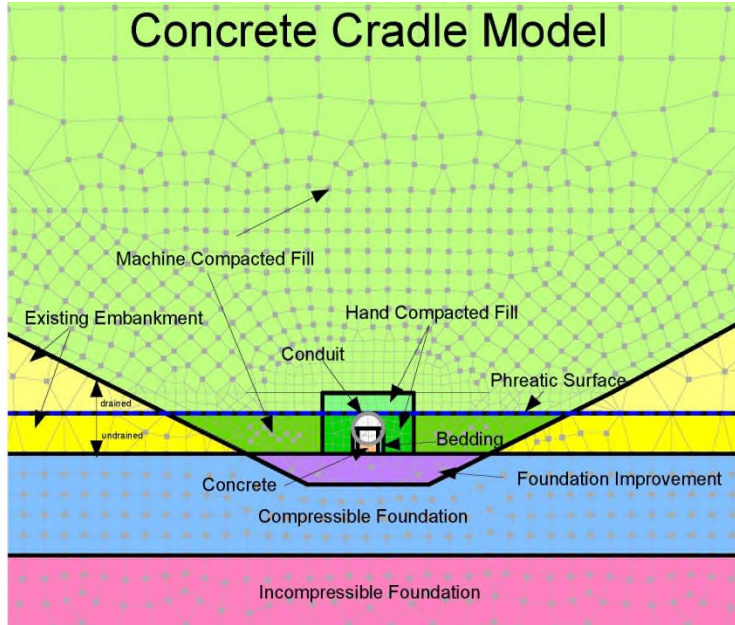


Figure 4 - Concrete Cradle Configuration

Concrete Encased Configuration

The concrete encased configuration shown details the different zones which are typically constructed in the field. With this method, the trench is excavated first, and then compacted with heavy duty compaction equipment to the springline of the conduit. A trench with sloped sides is then cut into the compacted fill. The pipe is placed on supports in the trench and the trench is filled with concrete. A low-slump concrete is placed over the pipe.

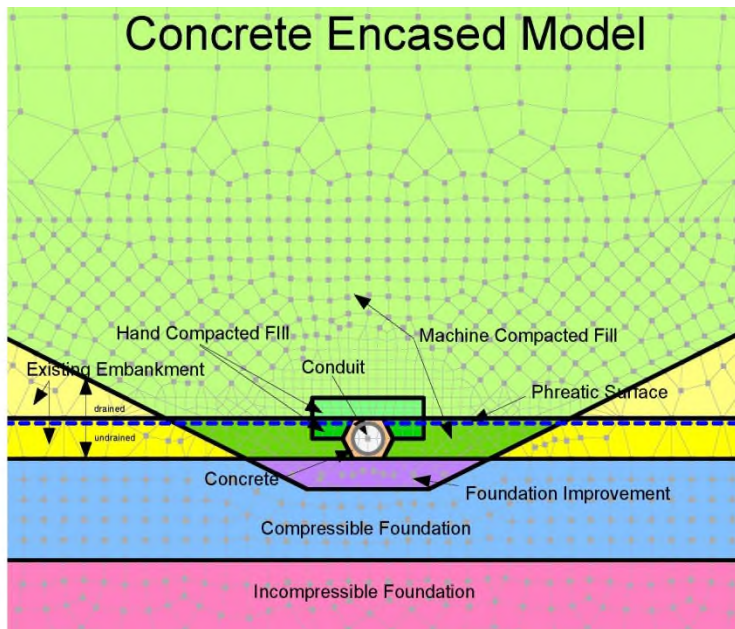


Figure 5 - Concrete Encased Configuration

Results

Model results indicate that stress levels resulting from outlet works replacement are influenced by the outlet configuration. Multiple indicators of outlet configuration performance were evaluated from the model results. These include settlement, low stress zones, and high stress zones. Furthermore, the low and high stress zones are directly related to settlement of the backfill material in combination with soil properties.

Settlement

The soil stress behavior of the outlet configurations is directly related to settlement and associated bridging effects. The following table and figure compares maximum settlement for the four (4) outlet configurations. These values include settlement experienced both during construction and following construction for a period of 1-year. For all outlet configurations, the maximum settlement occurs adjacent to the conduit in the hand compacted zone located below the phreatic surface.

Table 3 – Maximum Settlement	
Configuration	Settlement
Soil Bedding	0.67 ft
Field Cast	0.87 ft
Concrete Cradle	1.00 ft
Concrete Encased	0.33 ft

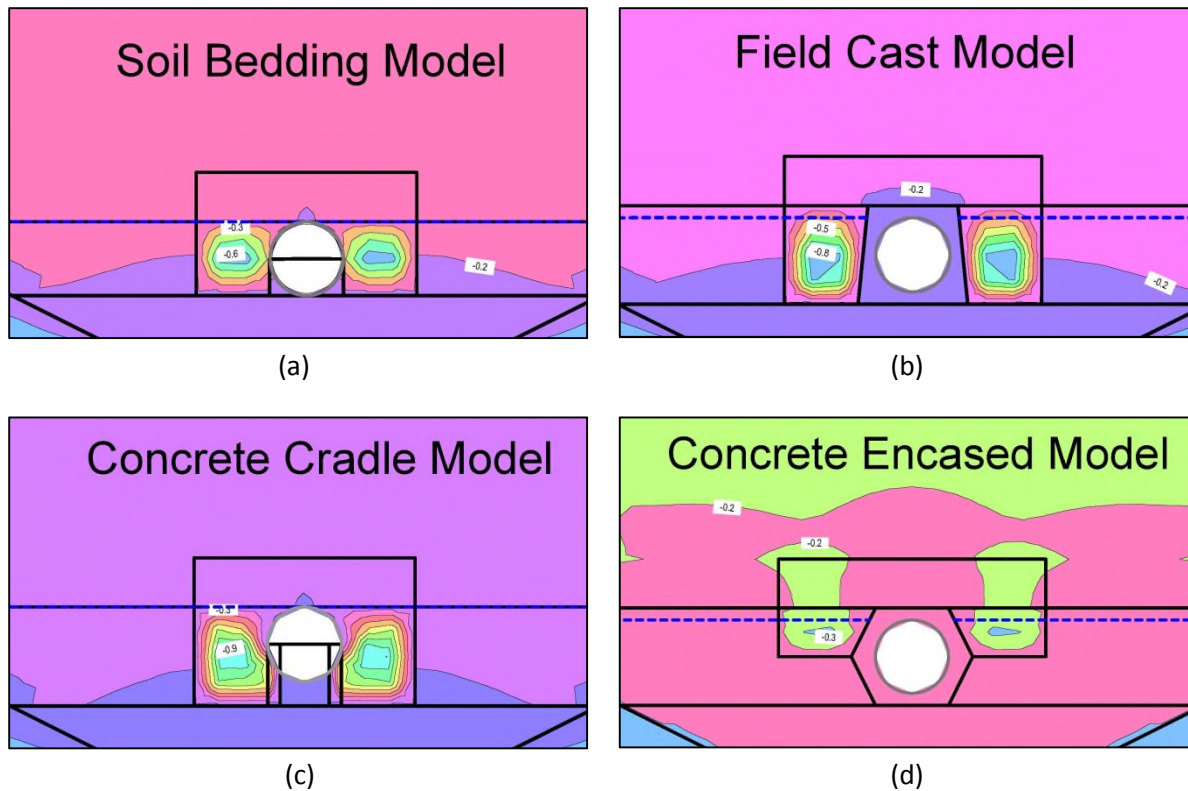


Figure 6 – Outlet Configuration Comparison Settlement, feet

Settlement magnitudes appear to correlate with the zone of compressible hand compacted backfill. For configurations with smaller zones of hand compacted backfill, lower settlements were generally observed.

Low Stress Zones

The development of low stress zones are key indicators of potential failure mechanisms. Low stresses are indicative of soil arching or bridging above the low stress area and results in soil zones less resistant to piping erosion and hydraulic fracturing. Low stress zones also result in reduced confining pressures which may result in lower soil strengths. The following series of figures compare low stress areas for the four outlet configurations based on Total Y stresses (Figure 8) and Total Minimum Stresses (Figure 9). The Y-Stress contours illustrate stresses in the vertical or Y-direction, while the Total Minimum Stress contours illustrate minimum stresses calculated from the following equation (SIGMA/W, 2007):

$$\sigma_{min} = \frac{(\sigma_y + \sigma_x)}{2} - \sqrt{\left[\frac{(\sigma_y - \sigma_x)}{2}\right]^2 + \tau_{xy}^2} \quad (1)$$

Where:

σ_{min} = minimum total stress, psf

$\sigma_{x,y}$ = total stress in respective direction, psf

τ_{xy} = shear stress, psf

The following figure presents an example Mohr's Circle taken directly from the model that illustrates the stresses shown in Equation (1).

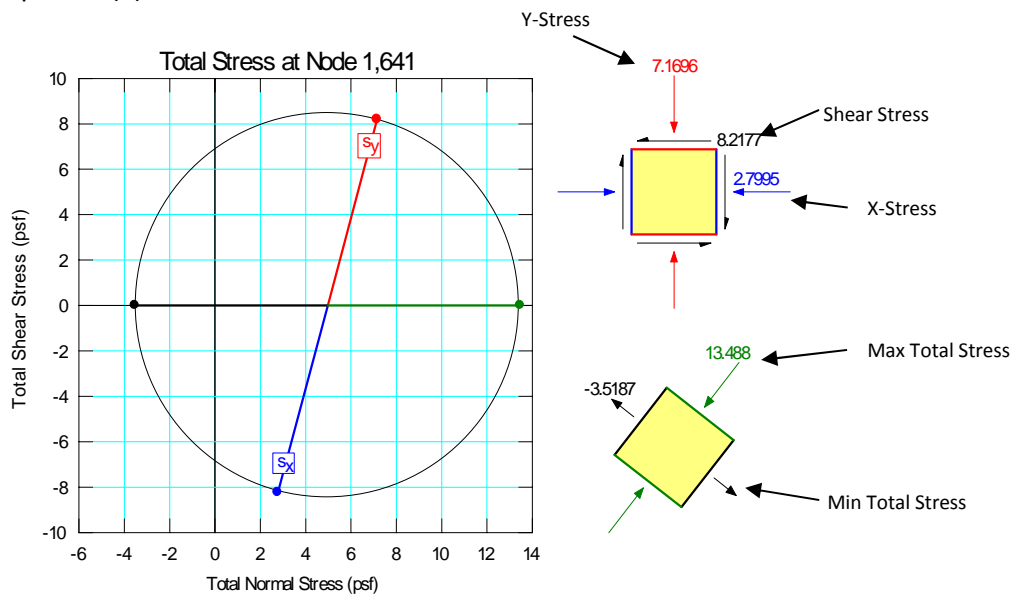


Figure 7 - Example Mohr Circle Illustrating Stresses

The following results show the location of the low stress zones for each of the outlet configurations is located almost entirely within the hand compacted soil zone. For the soil bedding and concrete cradle configuration, the low stress zone extends completely to the conduit, while the low stress zone for the field cast and concrete encased configurations do not. The results also show the size of the low stress zone is noticeably smaller for the field cast and concrete encased configurations. Smaller low stress zones indicate lower potential for piping and hydraulic fracturing, especially when those zones are located some distance from the conduit. The locations and size of low stress zones appear to be directly related to the hand compacted soil zone.

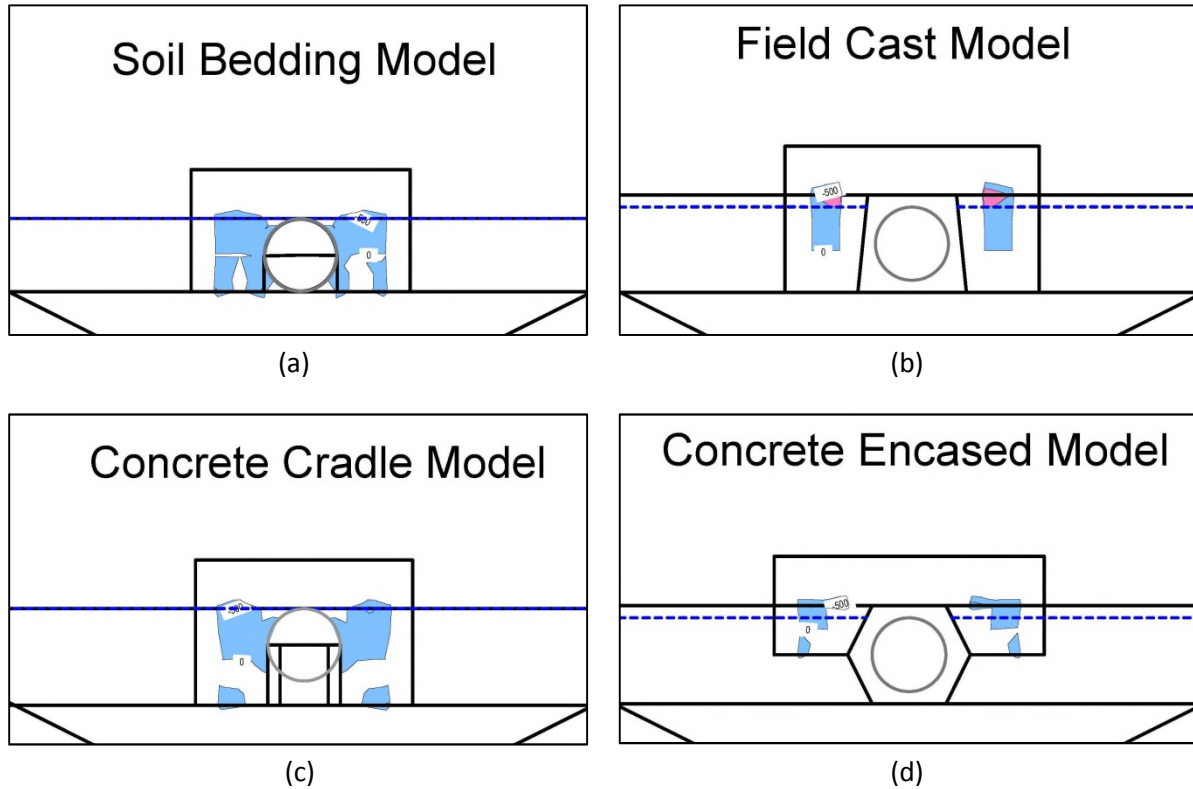


Figure 8 – Outlet Configuration Comparison Y-Stress Contours \leq zero psf

The figures also show the low stress zones consist primarily of zero stress, however negative stresses were also observed. This was especially the case of the Total Minimum Stress contours (Figure 9). Negative stresses are indicative of developed tension zones. Typically soils are relatively weak in tension and therefore tensile strength of soils is directly related to crack development and propagation.

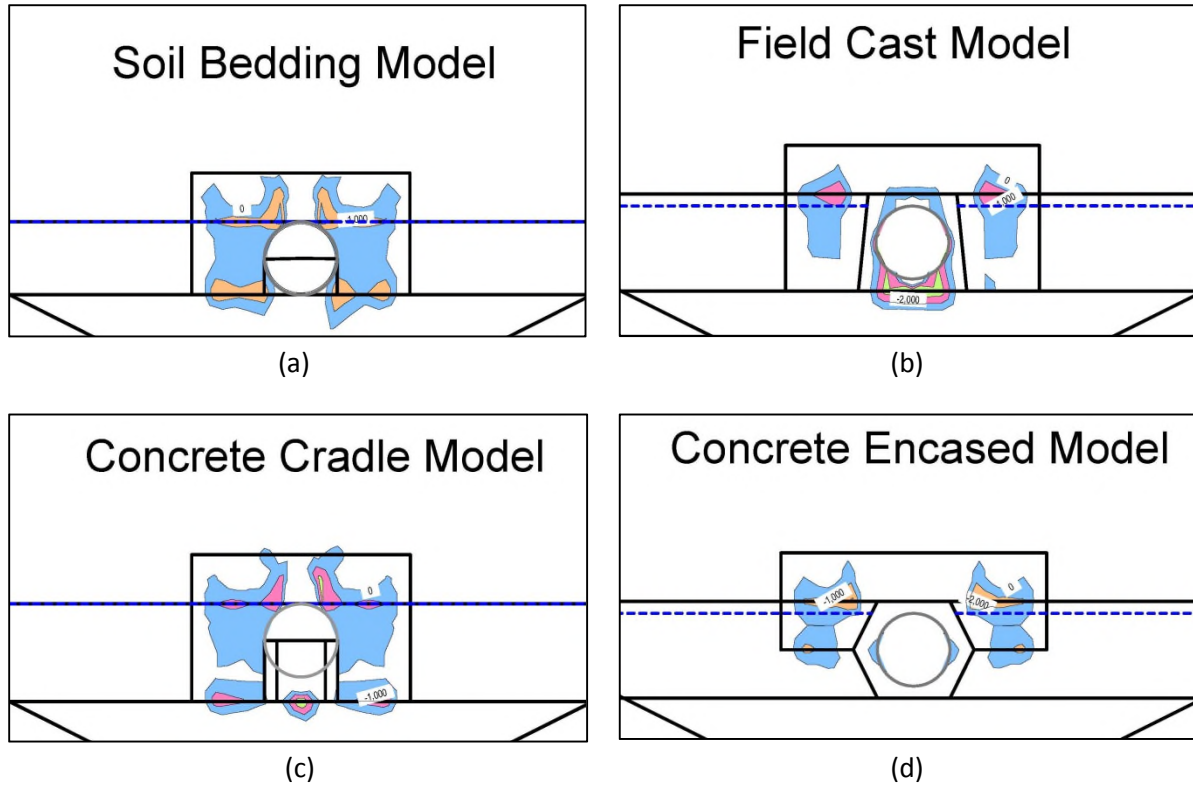


Figure 9 –Outlet Configuration Comparison Minimum Total Stress Contours \leq zero psf

Figure 10 compares Mean Total Stresses of the four outlet configurations. As zones of low stress are the primary concern, these figures show stresses less than or equal to zero. Mean Total Stress is the average of all stresses and is calculated from the following equation (SIGMA/W, 2007):

$$P = \frac{(\sigma_x + \sigma_y + \sigma_z)}{3} \quad (2)$$

Where:

P = minimum total stress, psf

$\sigma_{x,y,z}$ = total stresses associated with each respective direction

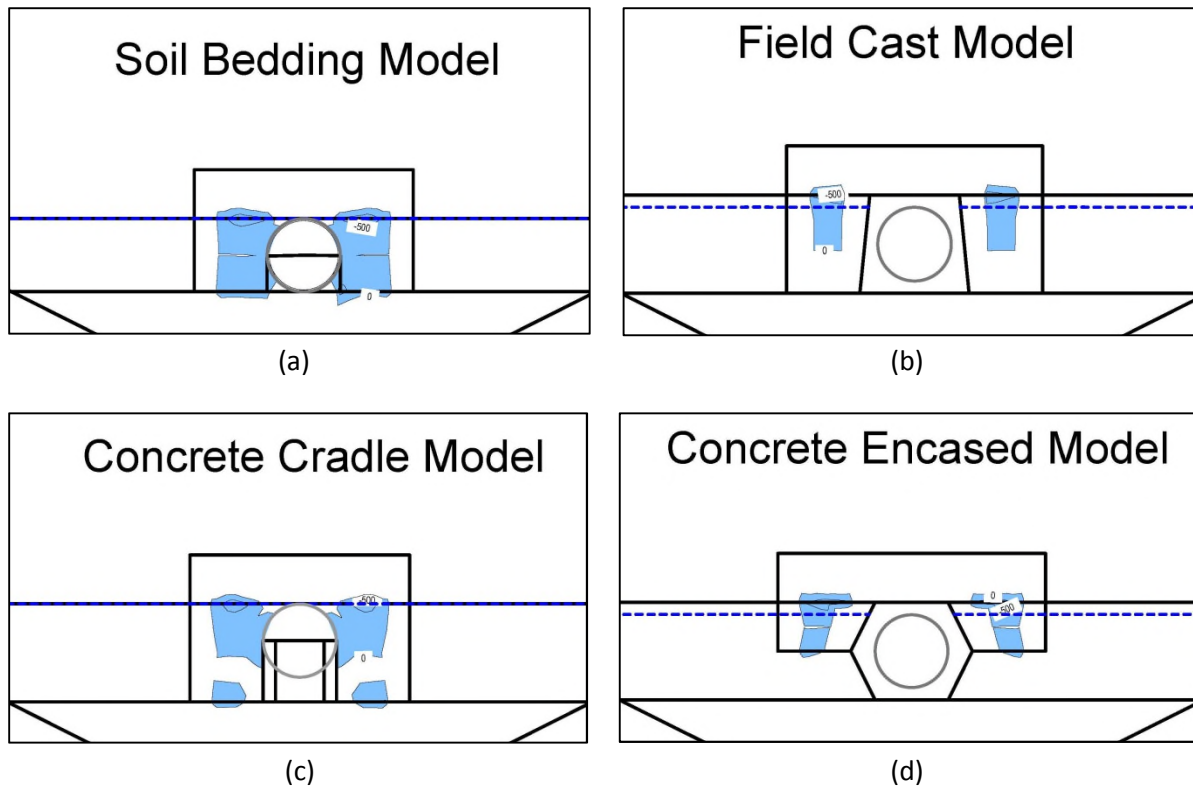


Figure 10 – Outlet Configuration Comparison Mean Total Stress Contours \leq zero psf

The following table summarizes low stress results. The table shows that for all stress types examined, tension zones form. This is an indicator of crack development and propagation potential which depends on the size, location, and orientation of the tension zones.

Table 4 – Minimum Stresses			
Configuration	Y-Stress, psf	Minimum Total Stress, psf	Mean Total Stress, psf
Soil Bedding	-588	-2,482	-849
Field Cast	-1,036	-3,218	-753
Concrete Cradle	-654	-3,029	-869
Concrete Encased	-832	-2,237	-750

Note: Values listed are minimum stresses, regardless of location.

High Stress Zones

High stress zones are indicative of areas where soils may be overstressed, resulting in failure mechanisms. The following series of figures compare the high stress zones for the four outlet configurations based on Total Y stresses (Figure 11) and Total Maximum Stresses (Figure 12). As with the low stresses, Y-stresses represent stresses in the vertical direction and Total Maximum Stresses are calculated from the following equation (SIGMA/W, 2007):

$$\sigma_{max} = \frac{(\sigma_y + \sigma_x)}{2} + \sqrt{\left[\frac{(\sigma_y - \sigma_x)}{2}\right]^2 + \tau_{xy}^2} \quad (3)$$

Where:

σ_{max} = maximum total stress, psf

$\sigma_{x,y}$ = total stress in respective direction, psf

τ_{xy} = shear stress, psf

For these figures, high stress is defined as total stress exceeding the average overburden pressure. These results show that all configurations exhibit high stresses in the vicinity of the conduit. The configurations also exhibit elevated stresses near the interface of the hand compacted soil zone. Lower high stresses and smaller high stress areas indicate lower potential for overstressing of the embankment and foundation soils and related movement.

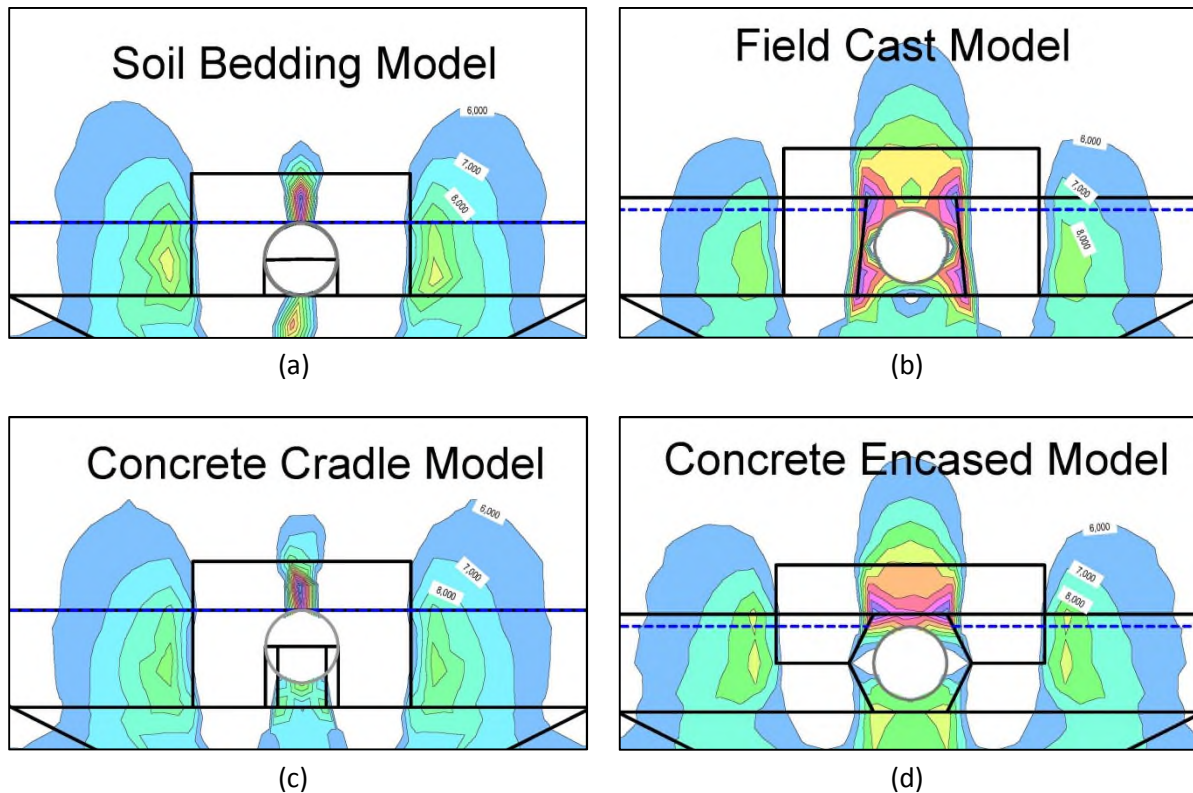


Figure 11 –Outlet Configuration Comparison Y-Stress Contours \geq overburden pressure

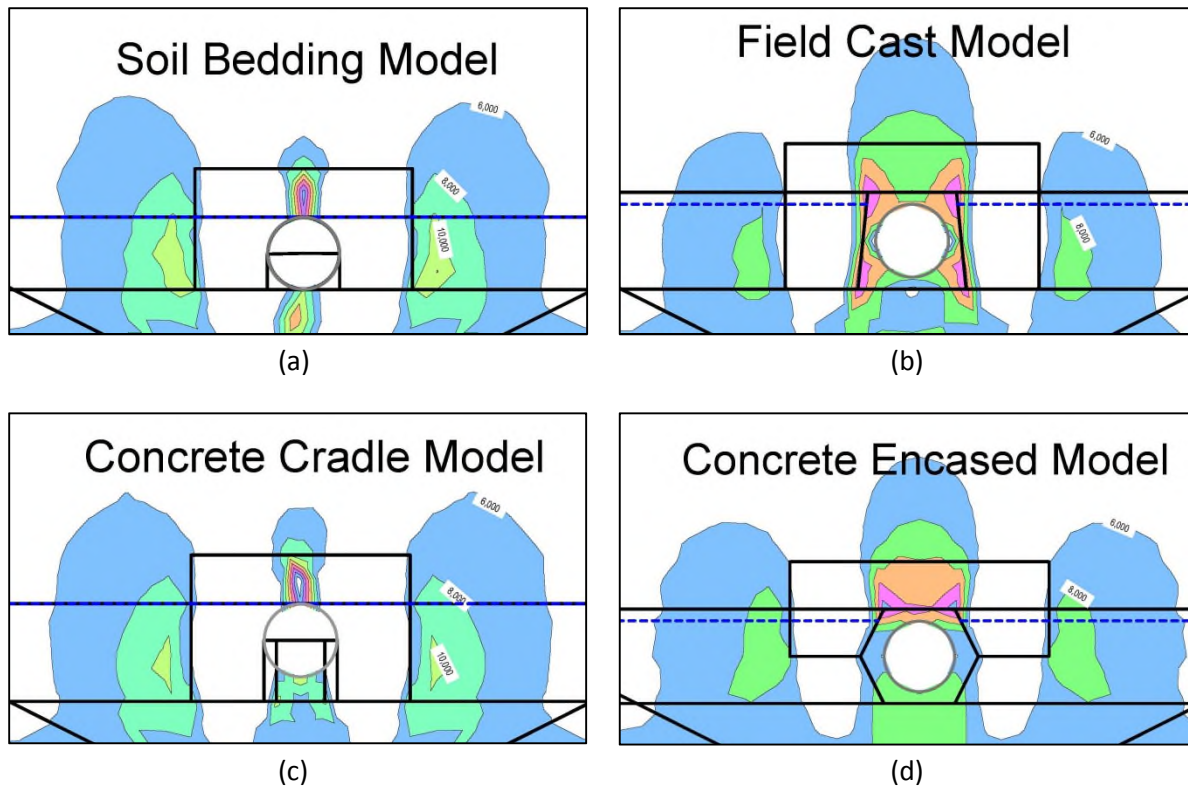


Figure 12 –Outlet Configuration Comparison Maximum Total Stress Contours \geq overburden pressure

The following table summarizes maximum stresses. The table shows that peak stresses for the field cast and concrete encased configurations are significantly lower than those associated with the soil bedding and concrete cradle configurations.

Configuration	Y-Stress, psf	Maximum Total Stress, psf	Mean Total Stress, psf
Soil Bedding	19,215	19,215	10,926
Field Cast	13,737	14,241	7,384
Concrete Cradle	21,890	21,944	12,307
Concrete Encased	14,735	14,988	8,463

Note: Values listed are maximum stresses, regardless of location.

Concrete Encased Outlet Configuration Performance

Settlement, size and location of low stress zones, and magnitude and location of high stress zones are all indicators of potential problem areas in the soils adjacent to outlet conduits. As the previously presented figures illustrate, the concrete encased outlet configuration performs well in each of these areas when compared to other common outlet configurations, and in some instances outperforms other configuration types. The concrete encased outlet configuration demonstrates the potential for

relatively low settlements, resulting in a stress distribution that minimizes low stress and tension zones and reduces the potential for over-stressing. This results in an outlet configuration with low potential for bridging, piping, and hydraulic fracturing.

Based on the model results, it is apparent the performance of this configuration is due to the ability to machine compact backfill material prior to conduit installation. This results in a smaller zone of hand compacted material, which is directly correlated to the settlement and stress distribution. Incorporating rigorous density control of the hand compacted fill adjacent to the conduit and possibly using wheel-rolled compaction to ensure higher densities would significantly improve the performance of the concrete encased configuration.

Preliminary Sensitivity Analysis

As discussed previously, several factors may influence the performance of the outlet configurations. For this reason a preliminary sensitivity analysis of some of the factors was completed using the concrete encased conduit outlet configuration. For all of the sensitivity comparisons, Total Minimum Stresses have been utilized as the most relevant measure of performance.

Trench Width

The first variable analyzed was trench width. Trench width is important as it must be wide enough to accommodate construction equipment and small enough to limit the volume of material removal to a reasonable amount. The following figures compare trench bottom widths of 6 and 12 feet. The results indicate that both trench widths behave similarly with no distinct advantage of using one over the other.

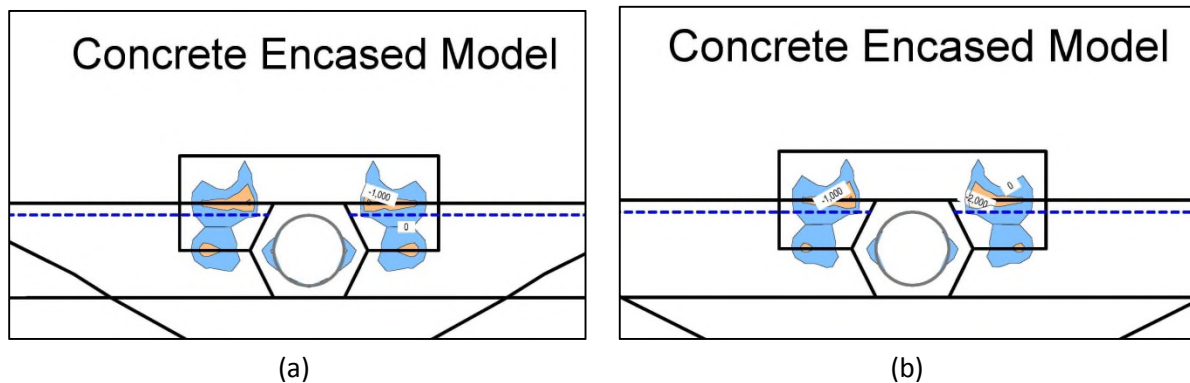


Figure 13 –Trench Width Comparison Minimum Total Stress Contours \leq zero psf, (a) 6 ft wide, (b) 12 ft wide

Excavation Side Slopes

The next variable examined was the slope angle of the conduit replacement excavation. Two slopes were analyzed: 1 H: 1V and 2 H: 1V. Slope angles also influence the volume of material removal and influence stresses along the embankment/backfill interface. The following figures compare the two slope angles. Results show that at the steeper slope (1:1) low stress zones are larger adjacent to the conduit. It was also found that low stress zones develop along the excavation/backfill interface (not shown). Due to the presence of these additional low stress zones, flatter slope angles are preferred. Flatter slopes may also allow for increased constructability compared to the steeper 1:1 slopes.

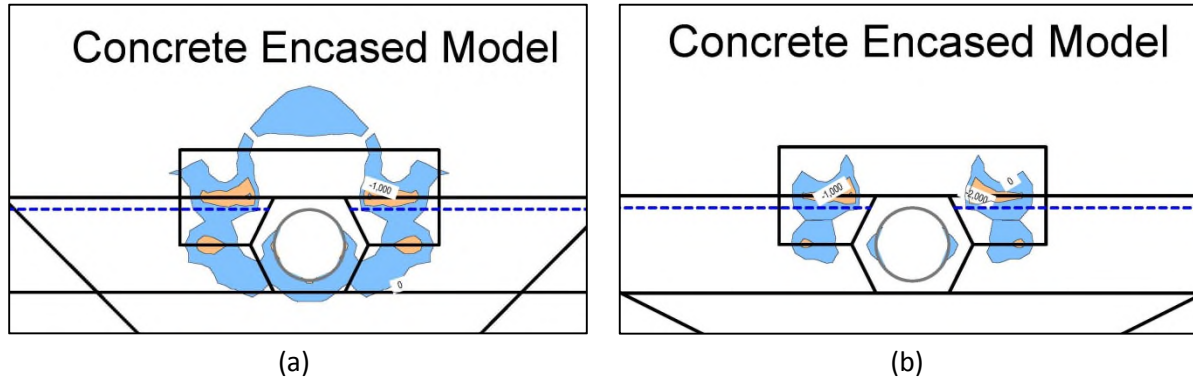


Figure 14 – Excavation Slope Comparison Minimum Total Stress Contours \leq zero psf, (a) 1H:1V, (b) 2H:1V

Foundation Improvement

The effect of foundation improvement was also examined. Results indicate that when foundation improvement is incorporated into outlet works replacement, the zone of low stress becomes significantly smaller. This results from the combination of the foundation improvement itself and the volume decrease of the hand compacted zone due to the wider excavation. The foundation improvement also results in reduced maximum settlement on the order of 27% and improves constructability.

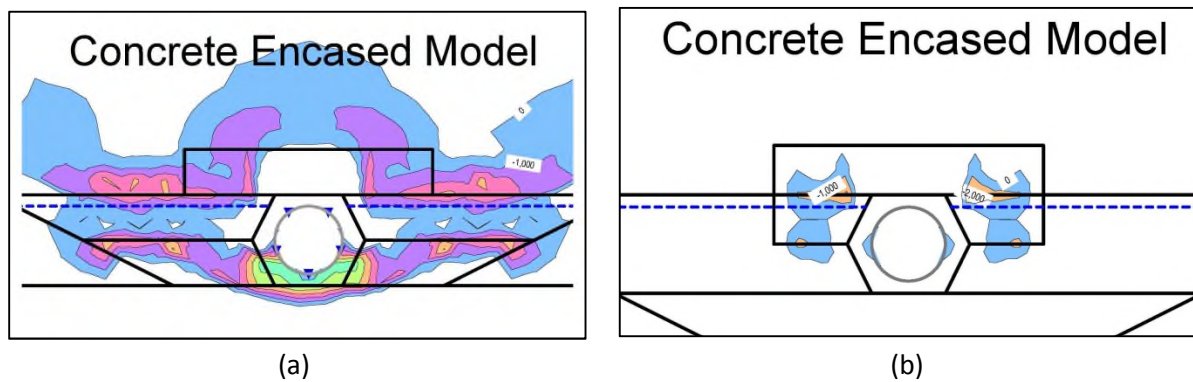


Figure 15 – Foundation Improvement Comparison Minimum Total Stress Contours $<$ zero psf, (a) no improvement, (b) with improvement

Embankment Height

The last variable examined was embankment height. Results indicate that higher embankments result in higher stresses and therefore a smaller low stress zone, however development of tension zones tend to increase with embankment height. While higher dams may pose a more significant threat of failure, smaller dams may be prone to piping and hydraulic fracturing due to the increased low stress zone.

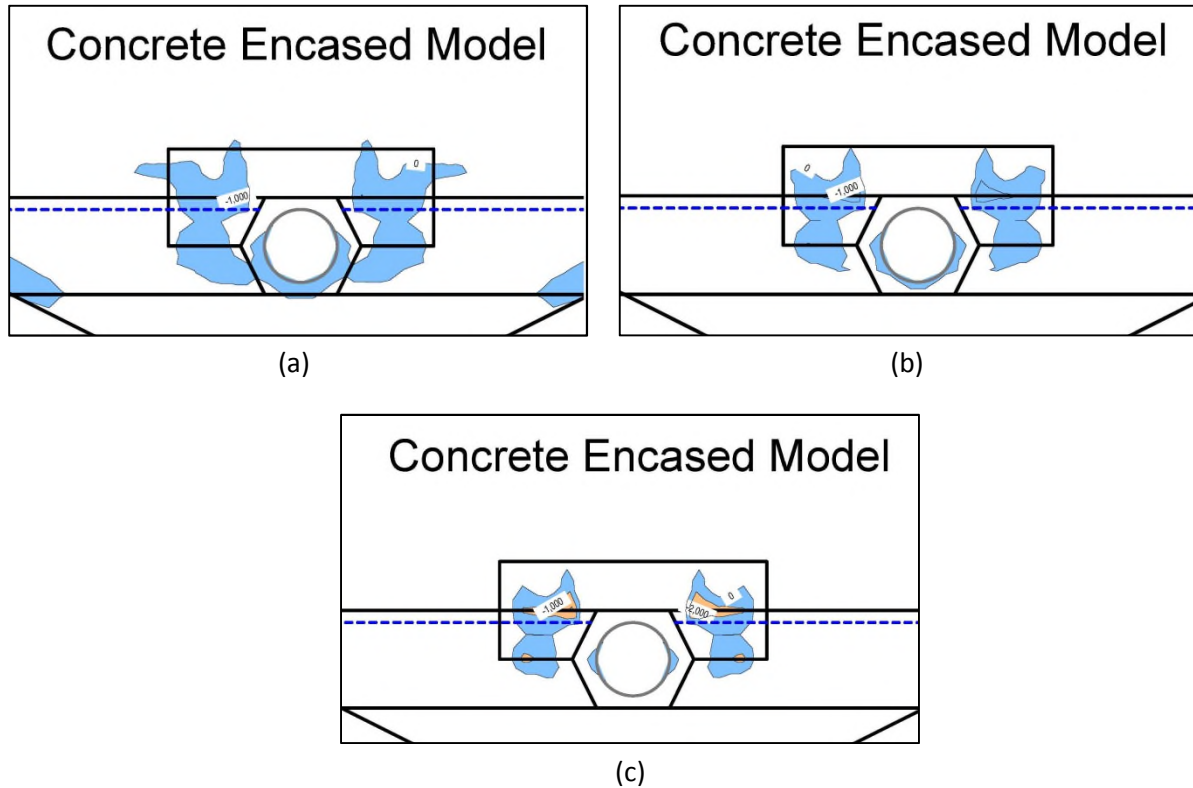


Figure 16 – Embankment Height Comparison Minimum Total Stress Contours < zero psf, (a) 20 ft, (b) 35 ft, (c) 50 ft

Conclusion

When considering outlet works replacement of earthen embankment dams, selecting the appropriate outlet configuration is critical. This is especially important with regards to minimizing potential for piping and hydraulic fracturing that could lead to dam failure. Based on an analysis of four selected outlet configurations the concrete encasement outlet configuration is a viable alternative to commonly used outlet configurations as it performs well with regards to stresses and settlements. Based on model results, the primary factor that influences outlet soil stresses is the level of compaction associated with the backfill material. Due to the difficulty to compact and test soils in the haunch area under the conduit, the authors recommend the soil bedding configuration should generally be avoided. Minimizing zones of lower compaction around the conduit is a very important aspect for limiting zones of low soil stresses.

Based on preliminary sensitivity analysis the following key observations were noted:

- Design considerations that minimize hand-compacted areas provide significant benefit in minimizing development of low stress areas adjacent to the conduit.
- The area beneath and adjacent to the outlet conduit should receive special attention during construction to attain and verify levels of compaction that are similar to adjacent machine compacted areas.
- When over-excavation for foundation improvement is included, trench width has little influence on stresses and should be selected based on constructability and economics.
- Excavation side-slope influences the low stress zones. Steeper slopes tend to result in more low stress zones than flatter slopes. Flatter slopes may also aid in constructability.
- Foundation improvement can provide significant reduction of low stress zones and settlement.
- Zones of low stress tend to increase as embankment height decreases, however concentrated tension zones that could lead to cracking tend to increase with embankment height.

Recommendations for Future Research

Many factors influence piping and hydraulic fracturing associated with low stress zones in earthen embankment dams. This study focused on comparing outlet configurations to investigate the validity of the concrete encased configuration. Future work could build on this study and look further at other factors that influence the performance of the outlet works. Future research could include:

- Examining the influence of flexible versus rigid conduit material
- Influence of phreatic surface
- Influence of soil parameters
- Examining how the depth of foundation improvements influences performance
- Thickness of foundation soils and effect of foundation compressibility
- Influence of time steps associated with each lift placement

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