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고속도로 하부 횡단 배수시설로 사용되는 파형 플래스틱 관의 덮개 요건

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Cover Requirements for Corrugated HDPE and PVC Pipes Used for Cross-drains in Highway Construction

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Abstract: This project investigated the use of two types of thermoplastic pipes, High-Density Polyethylene (HDPE) and Poly-vinyl Chloride (PVC), as cross-drains under highways. Pipes ranging from 0.3 m (12 in.) to 1.5 m (60 in.) in diameter were evaluated under deep fills, minimum cover, and construction equipment loads. In addition to a comprehensive literature review, an analytical study into the allowable fill heights for thermoplastic pipes was conducted. Based on the study findings, recommendations regarding how and when thermoplastic pipe should be installed are provided.

Key Words: Finite element analysis, Maximum cover, Minimum cover, Thermoplastic

1. Introduction

The three most common culvert materials currently being used are concrete, aluminum, and steel (Normann et al. 2001). The U.S. Federal Highway Administration (FHWA) regulations state that as of December 2006, equal consideration must be given to the use of alternative pipe materials such as plastic and corrugated aluminum as long as they are judged to be satisfactory based on both engineering and economic analyses (FHWA 2006). Therefore, the use of thermoplastic pipes for highway applications has begun to increase (Gassman et al. 2005). Thermoplastic pipes, however, are still relatively recent replacements for steel and concrete in many civil engineering projects (Sargand et al. 2002) and as with any new material, civil engineers must be convinced that the structural and long-term performance of thermoplastic pipes will be satisfactory in critical highway applications (Gassman et al. 2005, Sargand et al. 2002). According to Sargand et al. (2002), the common concerns about thermoplastic pipes are related to the allowable maximum fill height, mininum cover requirement, the length of time required for stabilization of the culvert responses, and the recommended design method for buried thermoplastic pipe. It is therefore important to quantify cover requirements for thermoplastic pipes by characterizing the performance of both the thermoplastic pipes themselves and soil-pipe interaction (Gassman et al. 2005).

주요어: 유한요소해석, 최대매설깊이, 최소매설깊이, 플래스틱

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2. Objectives and Scope

The primary objective of this study was to evaluate cover requirements of high-density polyethylene (HDPE) and polyvinyl chloride (PVC) pipes for use as cross-drains under highways. The evaluation process was accomplished by executing the following tasks: 1) collect and synthesize previous research, as well as recommendations from HDPE and PVC pipe manufacturers; and 2) analytically evaluate maximum and minimum cover recommendations.

3. Literature Review

This study comprehensively reviewed relevant materials for both HDPE and PVC pipes for use as drainage material under highways. These have included a set of fill height tables for HDPE pipes (Ardani et al. 2006), recommended test and design methods for thermoplastic drainage pipes (NCHRP 2009), the most recent design manual for HDPE pipes from the Plastics Pipe Institute (Gabriel 2010), and an evaluation of the use of HDPE and PVC pipes in highway cross-drains (Stuart 2011).

It is important to note that HDPE and PVC pipes are viscoelastic materials. They, therefore, respond very differently to applied loads than linear, elastic materials (Gabriel and Goddard 1999). Flexible pipes such as HDPE and PVC pipes are defined as pipes that can deflect by up to 2% without any structural distress, which helps them carry a greater soil load (AWWA 2002). Rigid pipes such as concrete pipes on the other hand must support their earth load solely as a result of the inherent strength of the pipe (Jeyapalan and Boldon 1986). It, also, should be noted that the performance limits for flexible pipe include deflection, wall buckling, wall stress, and wall strain (Goddard 1994), whereas the predominant design factor limiting rigid pipes is strength.

Maximum cover limits for thermoplastic pipe installations vary widely between specifying agencies, pipe manufacturers, and state DOTs. The most widely used maximum fill heights specified by state DOTs are between 3 m (10 ft) and 6 m (20 ft) (Ardani et al. 2006).

Minimum cover limits deal with live loads caused by moving vehicles in addition to the earth load. During the construction, the effects of construction equipment crossing over the pipe must also be considered. Most state DOTs specify minimum fill heights in the range of 0.3 m (1 ft) to 0.9 m (3 ft) for highway application (Ardani et al. 2006), but the temporary construction cover is typically specified to be 0.3 m (1 ft) to 0.6 m (2 ft) higher in order to consider the effects of heavy equipment during construction.

4. Analytical Study

4.1 Modeling Methodology

This study was based upon FE analyses that incorporated nonlinear soil models and parameters, the time-dependent material properties of HDPE an dPVC, and the geometric nonlinear behavior of the soil-pipe system. The Duncan and Selig soil models (Duncan and Chang 1970, Selig 1988) have been incorporated into CANDE-2007 (NCHRP 2008), which was developed as a result of research sponsored by AASHTO in cooperation with the FHWA.

The finite element (FE) modeling was executed using Abaqus (2011). Figure 1 shows a schematic FE model. Only half of the system (Fig. 1a) was modeled in the maximum cover study as the soil-pipe system is symmetrical. The results from exploratory trial FE analysis runs showed that it was not necessary for the lateral and top boundaries to extend three times the pipe diameter horizontally from the center of the pipe and three times the pipe diameter vertically above the crown (NCHRP 2008, Kang et al. 2009). For the minimum cover study, full soil-structure models were needed in order to impose unsymmetrical live loads, as illustrated in Fig. 1b. Table 1 presented the time -dependent material properties of the HDPE and PVC used in this study (AASHTO 2002, PPI 2003, PP 2003). The unit weight (ɣ) of the pipe materials was taken to be 9.4 kN/m3 (59.3 pcf). The unit weight of the soil was assumed to be 19 kN/m3 (120 pcf).

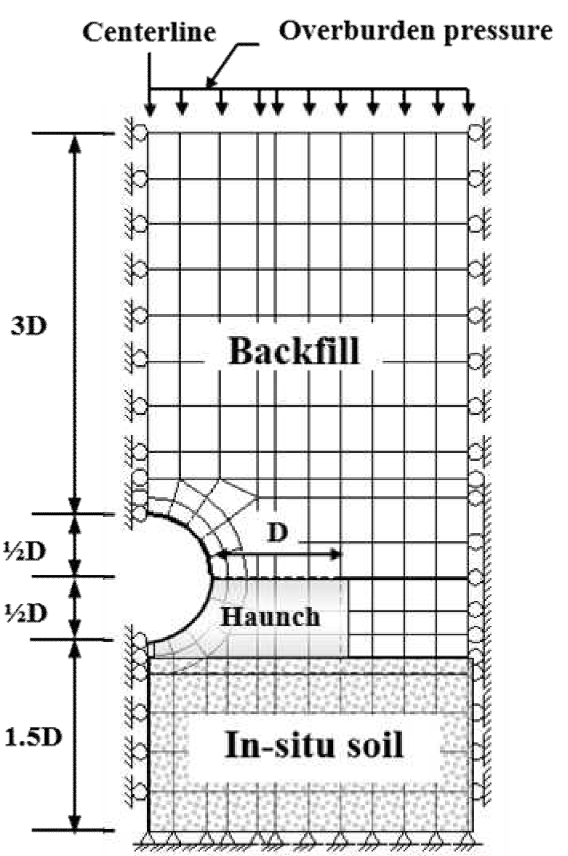


Fig. 1(*a*) Schematic Finite Element Model for Evaluating Maximum Fill Heights (*D*= pipe diameter)

Full-scale field tests carried out by the Florida DOT (Arockiasamy et al. 2004) were employed to calibrate and validate the FE modeling methodology for the maximum and minimum cover evaluation. Kang et al. (2013a, 2013b) showed that the pressure measured from the field tests has excellent agreement with those from FE analyses.

4.2 Fill Height Evaluation Basis

Two critical performance parameters of thermoplastic pipes in the design are the maximum wall stresses and vertical deflections. The maximum stresses were evaluated against the yield stresses of PVC and HDPE provided in Table 1. Deflection can be quantified in terms of the percentage decrease or increase in the pipe diameter (D) and in pipe design the vertical deflection is used as a benchmark and limited by AASHTO LRFD (2007) to 5%.

Table 1. Time-dependent material properties of ated HDPE and PVC pipes (AASHTO LRFD 2007).

Pipe Type	Initial			50-Year		
	E_{ini}	n_{ini}	S_{yi}	E_{50}	n_{50}	S_{y50}
	MPa (psi)		MPa (psi)	MPa (psi)		MPa (psi)
PE pipe AASHTO M 294	758 (110,000)	0.35	21 (3,000)	152 (22,000)	0.45	6 (900)
PVC pipe AASHTO M 304	2,758 (400,000)	0.30	48 (7,000)	965 (140,000)	0.30	26 (3,700)

The structural response under both the short-term and long -term properties was investigated, and the long-term properties controlled (Sargand et al. 2002, Kang et al. 2009, Kang et al. 2007). The section properties used for the corrugated PVC and HDPE pipes conformed to Section 12 of AASHTO LRFD. AASHTO LRFD specifies a 90% minimum compaction requirement for HDPE or PVC pipe backfill. The numerical analyses in this study were executed using several different compaction values for SW90 (gravelly sand compacted to 90%) and SW95 (gravelly sand compacted to 95%). Furthermore, the use of silty sand (ML) and silty clay (CL), were also considered in order to evaluate the effects of lesser quality backfill materials as the surrounding sidefill for a flexible pipe provides considerable support.

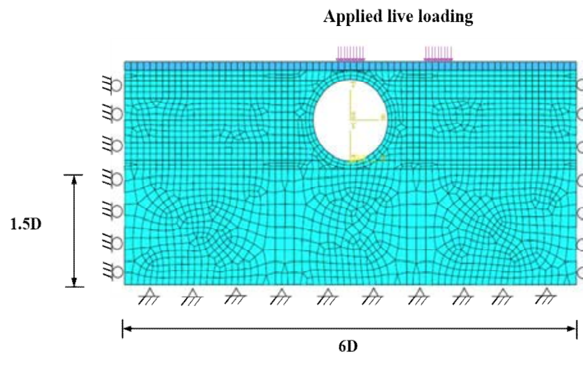


Fig. 1(b) Schematic Finite Element Model for Evaluating Minimum Fill Heights (*D*= pipe diameter)

4.3 Safety Factor

AASHTO LRFD (2007) specifies a Safety Factor (SF) equal to 2 for wall areas in the service load design of thermoplastic pipes and corrugated steel pipes (CSP). Therefore, the allowable stress, f_a, was calculated as follows:

$$f_a = \frac{f_u}{SF} \tag{1}$$

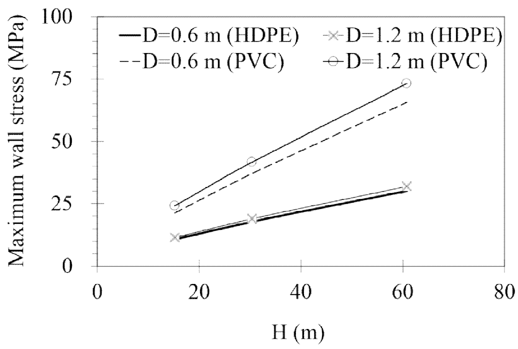
where f_a= allowable stress, fu= specified tensile strength, and SF = the safety factor, taken as 2.0. Since the deflection of the crown of flexible pipes becomes inverted and unable to resist additional loading at a deflection of approximately 20% (Moser 2001), the AASHTO deflection limit of 5% deflection inherently provides an *SF* of approximately 4. Therefore all of the analysis results presented in subsequent sections of this paper were based on *SF*=2 applied to stress limits presented in AASHTO LRFD (2007) or the 5% deflection limit.

4.4 Maximum Cover Limits

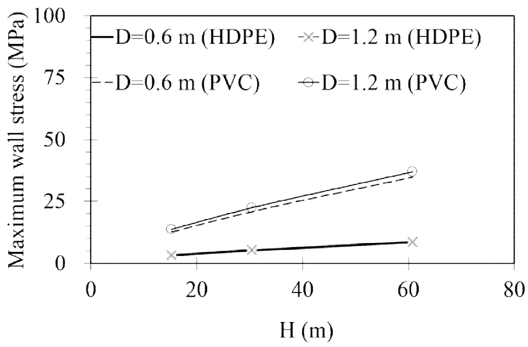
Fig. 2 illustrates the effects of pipe diameters for maximum wall stress. Two important findings are: 1) the maximum stresses were consistently higher in the larger diameter pipes than in the smaller diameter pipes as shown in Fig. 2; and 2) the strength limits from the long-term HDPE and PVC material properties (Table 1) governed the maximum fill heights.

The maximum fill heights for HDPE and PVC pipes were evaluated using the FE analyses (Fig. 3), and Table 2 presented the summary of the maximum fill height.

These values are generally in good agreement with the maximum cover limitations currently being used by state DOTs (Ardani 2006), PPI, and Uni-bell (2001).



(a)



(b)

Fig. 2 Effects of pipe diameters for maximum wall stress: (a) short-term and (b) long-term (soil properties= SW90).

Table. 2 Summary of Maximum Fill Heights Based on *SF*=2.

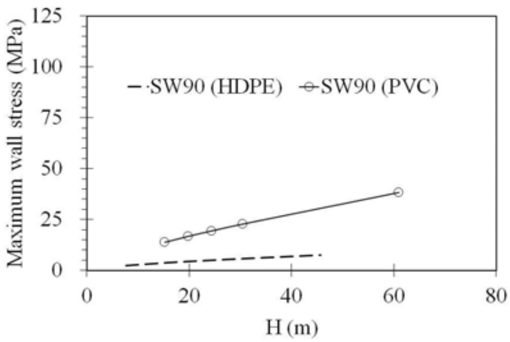
D	HDPE				PVC			
	SW95	SW90	ML95	ML90	SW95	SW90	ML95	ML90
0.3 (12)	20 (68)	12 (40)	14 (48)	9 (30)	35 (115)	23 (78)	23 (78)	14 (48)
1.5 (60)	18 (60)	12 (40)	14 (48)	8 (25)	20 (68)	14 (48)	15 (50)	11 (35)

Notes: 1) D= pipe diameter, units are m (in.); fill height units are m (ft).
2) More than 2 significant figures were used to calculate ft values.

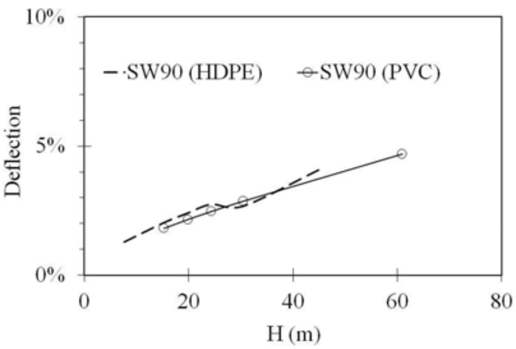
4.5 Minimum Cover Requirements Under Highway Live Loading

Without Pavement

The situation of a pipe being subjected to traffic loading without a pavement layer was investigated. AASHTO H20 and H25 live load configurations and surface pressures are used in this study (Fig. 4a). Various loading cases shown in Fig. 4b were investigated to identify the critical loading. Finally, the tandem H25 loading configuration oriented parallel to the pipe represented in Fig. 4b was determined to be the most critical loading case. As the transverse configuration is common for cross drain applications, the H25 loading oriented transverse to the pipe was also thoroughly analyzed.



(a)



(b)

Fig. 3 Effects of soil properties:
(a) maximum wall stresses for long-term, and
(b) deflections for long-term (pipe diameter= 1.5 m (60 in.), deflection limit= 5%).

Fig. 5 illustrates the variation of maximum wall stresses and deflection experienced by HDPE and PVC pipes versus the backfill height. These figures demonstrate that the wall stress limit was reached before the pipe reached a 5% deflection, which insist that wall stresses typically set the design criteria for minimum cover. The results for PVC pipes (Fig. 5) revealed the same trends as those for corrugated HDPE pipes. Table 3 shows the minimum cover with no pavement under live loads for various soil types and pipe diameters using the tandem H25 loading oriented parallel to the pipe. Here, the minimum fill heights are higher than those generally specified by the industry and state DOTs. This is due to the fact that this study used the AASHTO H25 & Alternative option as the live load. These results, with the factor of safety, provide a conservative minimum cover requirement for critical highway construction cases.

Table 3 provides the results for maximum wall stress and deflection using the most conservative tandem H25 loading parallel to the pipe axis.

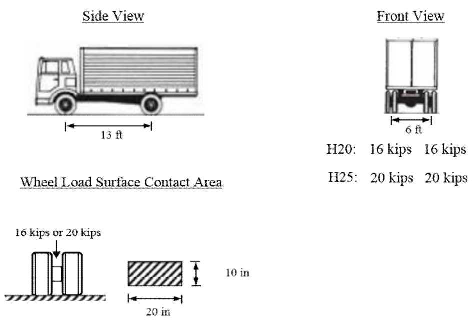


Fig. 4(a) AASHTO Live Loads (H20 and H25)

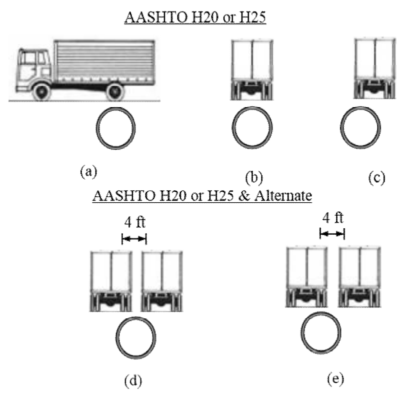
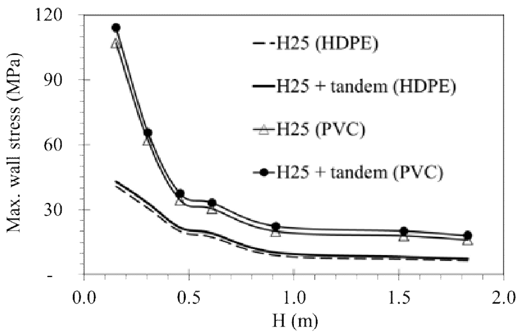
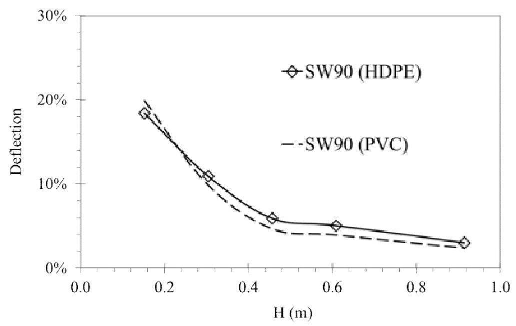


Fig. 4(b) Applied Live Load Cases



(a)



(b)

Fig. 5 Maximum wall stress and deflection under AASHTO live loads parallel to the pipe: (a) maximum wall stress (short-term, SW90, D=1.5 m (60 in.)), (b) effects of soil properties for deflection (long-term, D=1.5 m (60 in.)) (deflection limit= 5%).

The results presented in Table 3 for SW90 soil are generally in line with the minimum fill heights specified by the industry and by those state DOTs for which information is available (Ardani 2006). Perhaps surprisingly, the required fill height is not strongly dependent upon pipe diameter, but this is because the axial and flexural rigidities of the pipe walls increase with pipe diameter.

Including Pavements

The pavement thickness can be included as part of the minimum cover, and in this study the cover refers to the summation of the soil layer above the pipe and the pavement thickness.

Hard surfaced pavement can be categorized as either flexible or rigid. Flexible pavements are surfaced with bituminous materials such as asphalt concrete (AC), whose modulus of elasticity is 4.5 GPa (656,000 psi). In contrast, rigid pavements are composed of a portland cement concrete (PCC) surface course, with a modulus of elasticity of 24.8 GPa (3,600 ksi). Such pavements are much stiffer than flexible pavements due to the high modulus of elasticity of the PCC materials. The densities of both the AC and PCC were taken to be 2,323 kg/m3 (145 pcf).

Table 3. Minimum Cover Without Pavement Under H25 Live Loads (SF=2, Short-term) Unit: m (ft)

HDPE						
	SW90	SW80	ML90	ML80	CL90	CL80
LS1	0.45 (1.5)	0.55 (1.8)	0.51 (1.7)	0.76 (2.5)	0.73 (2.4)	1.06 (3.5)
LS2	0.9 (3.0)	1.3 (4.3)	1.22 (4.0)	1.60 (5.3)	1.50 (4.8)	1.90 (6.3)
PVC						
	SW90	SW80	ML90	ML80	CL90	CL80
LS1	0.36 (1.2)	0.45 (1.6)	0.39 (1.3)	0.55 (1.8)	0.61 (2.0)	0.76 (2.5)
LS2	0.9 (3.0)	1.2 (4.0)	1.2 (3.8)	1.5 (4.8)	1.3 (4.2)	1.40 (4.5)

Note: 1) SW= gravelly sand; ML= silty sand; CL= silty clay. 2) Analyses based upon 1.5 m (60 in.) diameter pipes. 3) LS1= H25 live load oriented transverse to the longitudinal axis of pipe; LS2= tandem H25 live loads oriented parallel to the pipe.

In this study, PCC and AC properties were used to represent the rigid and flexible pavements, respectively, with pavement thicknesses of 0.15 m (6 in.) and 0.3 m (12 in.). It is evident from Table 4 that the addition of pavement reduces the maximum wall stresses and, as expected, PCC is more effective than AC. Table 4 summarizes the minimum cover results based upon considering pavement rigidity.

4.6 Minimum Cover Requirements Under Construction Equipment Loading

Most state DOTs specify a cover ranging from 0.9 m (3 ft) to 1.2 m (4 ft) for construction loads to account for heavy construction equipment. Equipment travelling both parallel and perpendicular to the pipe was investigated in the FE models. The results showed that the critical loading cases consist of the equipment travelling perpendicular to the pipe, so the minimum covers for construction equipment loads were evaluated based on this loading.

The applications of highway live loading used to evaluating the minimum cover are different from those of construction equipment loading. First, short-term properties for HDPE and PVC were used in the analyses. Second, construction equipment loads are applied on temporary construction cover that is not fully compacted. The FE models in this study were developed using various soil properties and compaction levels, and SW60 was chosen to simulate the temporary cover above the crown. The structural backfill material around the pipe was chosen to be SW90 for the simulations.

As shown in Table 5, minimum cover under construction loads with SW90 structural backfill were governed by the wall stress limit. It, however, is clearly important for both wall stress and deflection limits to be checked during the design phase since the minimum cover is highly affected by the quality of installation around the pipe. Minimum cover requirements of thermoplastic pipes during the construction are independent of the pipe diameter, so Table 5 provides the maximum values among the minimum covers from all diameters.

5. Summary and Conclusions

The overall objective of this study was to assess the use of HDPE and PVC pipes for use as cross-drains under highways. The conclusions made consisted of

Table 4. Minimum Cover Including Pavement Under Tandem H25 Live Loads Oriented Parallel to the Pipe (SF=2; short-term properties). **Unit: m (ft)**

HDPE	PCC			AC		
	SW90	ML90	CL90	SW90	ML90	CL90
PT=0.15 (0.5)	1.1 (3.5)	1.2 (4.0)	1.5 (4.8)	1.2 (4.0)	1.5 (5.0)	1.9 (6.2)
PT=0.3 (1.0)	0.6 (1.8)	0.8 (2.5)	1.5 (5.0)	1.0 (3.2)	1.2 (3.8)	1.5 (4.8)
PVC	PCC			AC		
	SW90	ML90	CL90	SW90	ML90	CL90
PT=0.15 (0.5)	0.6 (1.8)	1.2 (3.8)	1.6 (5.2)	0.9 (3.0)	1.6 (5.2)	1.6 (5.3)
PT=0.3 (1.0)	0.5 (1.5)	0.6 (1.8)	1.5 (5.0)	0.7 (2.3)	1.2 (3.8)	1.6 (5.3)

Note: 1) SW= gravelly sand; ML= silty sand; CL= silty clay. PT= thickness of pavement.
2) Maximum values among D= 0.3 m, 0.9 m and 1.2 m were used.

integrating information gained from the literature review and the analytical study. The following general observations were made:

1) The strength limit using the long-term pipe material properties governed the maximum fill heights of the thermoplastic pipes.

2) Based on the results of our analyses and the tabularized minimum cover values presented in Tables 3 through 6, the following general observations were made:

- Pavement rigidity highly affects the minimum height of soil cover required for safe traffic operation and so minimum cover recommendations including pavement rigidity must be given careful consideration; and

- Minimum cover requirements under construction equipment loads are controled by the short-term properties of thermoplastics.

The cover requirements suggested as a result of this analysis could serve as a useful guideline for engineers, designers, and contractors tasked with specifying burial depths of thermoplastic pipes under highway applications.

The followings are recommendations based on this study:

1) Future work could include using viscoelastic material properties and 3D FE models to validate and refine the results from this study.

2) A well designed field instrumentations are necessary to verify cover requirements found by this analytical study.

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Table. 5 Minimum Cover Under Construction Equipment Loads. **(unit: m)**

Axle Load 80 -334 (kN)			Axle Load 334 – 667 (kN)		
AA	FE (HDPE)	FE (PVC)	AA	FE (HDPE)	FE (PVC)
SW60 used in the temporary fill and around the pipe & track pressure applied					
0.9	0.9	1.2	1.2	1.5	1.5
SW60 used in the temporary fill and SW90 in the structural backfill & track pressure applied					
0.9	0.6	0.9	1.2	1.2	1.2
SW60 used in the temporary fill and SW90 in the structural backfill & tire pressure applied					
0.9	2.1	2.1	1.2	2.1	2.1
SW60 used in the temporary fill and ML90 in the structural backfill & track pressure applied					
0.9	0.9	1.1	1.2	1.3	1.3
SW60 used in the temporary fill and ML90 in the structural backfill & tire pressure applied					
0.9	2.7	2.7	1.2	3.0	2.7

Note: 1) SW= gravelly sand; ML= silty sand; CL= silty clay. PT= thickness of pavement.
2) Maximum values among D= 0.3 m, 0.9 m and 1.2 m were used.

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