APPENDIX E – CULVERT DECISION-MAKING MATRICES

Liner Selection Matrix

This matrix summarizes properties, advantages and disadvantages of some of the liners commonly used in full-length, full-circumference repairs. Note that culverts with a slope greater than 1.5% can usually accommodate significant diameter reduction, as long as the diameter is not reduced within four feet of the inlet end. If the slope is greater than 1.5% and a liner will significantly reduce the pipe diameter, it is recommended the liner be terminated short of the pipe end and a new tapered or beveled inlet section be installed. See the sources noted below the table for more detailed discussion. More options and considerations for liner selection are also presented in the FLH Culvert Pipe Liner Guide and Specification, 2005.

Rehabilitation Type	Diameter Limits	Space Requirements for Installation	Shape, Deformation & Joint Discontinuity Tolerance	Structural Restoration	Diameter Reduction	Flow Bypass Required When Flow is Present?	Abrasion and Corrosion Resistance	Rough Comparative Cost	Other Factors and Limitations
Slip Liner - Segmental	Up to 158in. diameter for segmental; up to 72in. common	Small to moderate	Deformations and discontinuities in pipe can block insertion and limit diameter of the liner; host pipe must be round or semi-round	Depends on liner and annulus composition	Significant	Sometimes	Good	Low to Moderate; $50/lin.ft. for 18in. Diameter; $120/lin.ft. for 30in. Diameter; $400 to $500 per lin.ft. for 60in. diameter	Low safety concern for installers; Low environmental concern with installation process, in particular with low-density grout
Slip Liner - Continuous	Up to 72in. diameter common for continuous	Moderate to large							Moderate safety concern for installers; Low environmental concern with installation process, in particular with low-density grout; jointing can be labor intensive for fusion-welded
Fold-and-Form PVC or HDPE Liner (close-fit)	Up to 24in. diameter for PVC and 36in. for HDPE; Less than 15in. to 18in. most common; 4in. min.	Small	Deformations, discontinuities and pipe size changes will likely cause problems; host pipe must be round/circular shape	Does not restore structural integrity	Minimal	Usually	Very Good	Moderate to High; $100 to $300 per lin.ft.	Moderate safety concern for installers; Moderate environmental concern with installation process; specialized equipment and trained personnel needed.
Spiral-wound Liner	8in. to 120in. diameter, depending on type	Small	Host pipe must be round or semi-round; can tolerate minor discontinuities, deformations and pipe size changes	Depends on liner and annulus composition	Can be significant	Sometimes	Very Good	Moderate to High; $100/lin.ft. for 18in. Diameter; $570/ln.ft. for 78in. diameter; up to $750 per lin.ft. for larger diameters	Moderate safety concern for installers; Low environmental concern with installation process; larger manual systems require manned-entry; liners may become brittle in freezing temps; specialized equipment and trained personnel needed.
Cured-in-Place Pipe (CIPP)	12in. to 108in. diameter; 48in. or less most common	Small to moderate	Non-circular shapes, discontinuities and pipe size changes can be accommodated	May restore structural integrity, depending on liner wall thickness	Minimal for non-structural; Moderate for structural	Always	Very Good	High; $100/lin.ft. for 18in. diameter; up to $800 per lin.ft. for larger diameters	Moderate safety concern for installers; High environmental concern with installation process, in particular with contaminated water disposal and control of ground water infiltration; some resins may be toxic. Specialized equipment and trained personnel needed.
Spray-On Cement Mortar Lining	12in. to 24in. diameter most common; larger diameter possible	Small	Host pipe must be round or semi-round; can accommodate minor bends, discontinuities and imperfections in host pipe	Restores structural integrity if reinforced	Minimal for non-structural; Moderate for structural	Always	Poor	Low to Moderate; $100 to $150/lin.ft. for 24in. diameter; $250 to $350 per lin.ft. for 60in. Diameter	Low safety concern for installers; High environmental concern with installation process; specialized equipment and trained personnel needed; cement subject to breakdown if runoff is acidic or contains sulfates; infiltration control required; bends and long lengths can be problematic for pulling sled through pipe at necessary steady rate and verifying application thickness.
Spray-On Epoxy Lining	12in. to 24in. diameter most common; larger diameter possible						Fair		Low safety concern for installers; High environmental concern with installation process; specialized equipment and trained personnel needed; bends and long lengths can be problematic for pulling sled through pipe at necessary steady rate verifying application thickness.

<u>Sources</u>: FLH Bid History from various departments, 1997 to present; USDA Forest Service Report on Trenchless Technologies; Piehl, 2005; Caltrans Supplement to FHWA Practices Manual Bulletin No. 83-01, 2006; Central FLH Culvert Pipe Liner Guide, 2005; Virginia TRC Research Report No. FHWA/VTRC 08-R16.

<u>Notes</u>: Proceed to Page 7 - Appurtenances as necessary to complete the decision-making procedure. Expenses related to road closures and economic disruptions are not included in cost estimates presented here. If no suitable liner repair is available, the user should proceed to the localized man-entry repair or replacement selection matrix depending on circumstances.

Localized Man-Entry Repair Selection Matrix

This matrix presents cost estimates and limitations of some common localized man-entry repairs. See the sources noted below the table for more detailed discussion.

Rehabilitation Type	Cost Estimates Based on FLH Bid History	Rough Cost Estimates from Other Agencies	Maximum Size Limits	Other Limitations
Grouted Repair Sleeves or Short Cured-in-Place Sleeves (CIPP)	No Estimate Available	Low cost; $2000 to $5000 per CIPP repair for 18in. diameter	Up to 54in. diameter for CIPP; Up to 54in. for stainless steel; Up to 108 in. for PVC	Mechanical seals work poorly with helical and small diameter CMP; may fail if separated or offset joints present; CIPP available in 36 in. connectible lengths; can be used on deformed flexible pipes
Grouting voids	Medium Cost; $330/cu.yd.	Low cost; $10/lin.ft. for small voids; $100-$150/cu.yd. for large voids	N/A	Difficult to judge completeness of repair; toxicity with manned-entry
Crack Epoxy Injection/Mortar	No Estimate Available	Low cost	N/A	Toxicity with manned-entry; not recommended for cracks greater than 0.1in. wide
Crack/Spall Patching and Rebar Coating with epoxy grout	High Cost; General repair of concrete $860/sq.yd. or $2020/cu.yd.; epoxy coated rebar $1.30/lb	Low cost	N/A	Toxicity with manned-entry; hand-applied above or underwater via man-entry; repair may only slow deterioration or be cosmetic
Joint Sealing with Expansion Gasket Seal Ring	No Estimate Available	Low cost	Up to 216in. diameter	No more than 10% displacement tolerated; more applicable to RCP than flexible pipe
Invert Lining	No Estimate Available	Medium Cost	N/A	Difficulties tying into host pipe; cement is subject to breakdown if runoff is acidic; modified high-strength concrete mix required; steel plating is best for CMP and RCP, but corrosion is concern
Repoint Masonry	Low Cost; $55/sq.ft.	No Estimates Available	N/A	N/A

Sources: FLH Bid History from various departments, 1997 to present; USDA Forest Service Report on Trenchless Technologies; Piehl, 2005; Caltrans Supplement to FHWA Practices Manual Bulletin No. 83-01, 2006; Central FLH Culvert Pipe Liner Guide, 2005

Notes: Minimum diameter of 36 inches for man-entry relates to repair industry practices, and is more aggressive than the 48 inch minimum guideline established for FLH assessments by this culvert assessment and decision-making procedures manual. Proceed to Page 7 - Appurtenances as necessary to complete the decision-making procedure. Expenses related to road closures and economic disruptions are not included in cost estimates presented here.

Culvert Replacement Techniques Matrix

Replacement Type	Cost Estimates Based on FLH Bid History	Rough Cost Estimates from Other Agencies	Size Limits	Other Limitations
Pipe Bursting/Splitting	No Estimate Available	$100 to $200/lin.ft. for 18" diameter; $850 per lin.ft. for 48" diameter	Up to 48" diameter possible; up to 24" diameter common	Host pipe must be brittle; access at culvert ends for machinery; CMP can be difficult; existing pipe must be round or semi-round
Plug old pipe and install new via Horizontal-Directional Drilling (HDD)	Plugging an existing culvert $1600; No estimate available for drilling or augering methods	$100 to $300/lin.ft. for 18" diameter; $300 to $900 per lin.ft. for 36" diameter; $50 to $500/lin.ft. depending on size	Up to 48" diameter	Heavy equipment needed; ample access and space required at culvert ends for machinery and slurry pit, as well as full length of pipe (9' to 25' pit typ.); backstop necessary; boulders can obstruct and non-cohesive soils can collapse after drilling; must be round
Plug old pipe and install new via Horizontal-Auger Boring		$200/lin.ft. for 18" diameter; $1000 per lin.ft. for 60" diameter; $3-$6/in.diam./lin.ft.	Up to 72" diameter	Access and space required at culvert ends for machinery and slurry pit, as well as full length of pipe; backstop necessary; boulders can obstruct and non-cohesive soils can collapse; must be round
Plug old pipe and install new more shallow pipe or surface drain	No Estimate Available	No Estimate Available	Typically 30" diameter or less	Performance limitations typically associated with ditch relief culverts
Pipe Jacking/Ramming	Jacked 36 inch diameter concrete pipe $1150/ln.ft.	$260/lin.ft. for 24" diameter; $5000 to $6000 per lin.ft. for 10' diameter; ramming $3-$6/in.diam./lin.ft.; jacking $5-$15/in.diam./lin.ft.	24" to 48" diameter common for jacking (up to 10' diameter possible); 4" to 42" diameter common for ramming	Access and space required at culvert ends for machinery and slurry pit (10'-30' jack pit typ.); bulges and boulders can obstruct
Open-Trench Excavation	Roadway (channel) excavation $25/cu.yd. and shoulder excavation $60/cu.yd.; subexcavation $20/cu.yd.; shoring and bracing $90/sq.ft.; removing existing culvert $1200 to $13,000 (size and type dependent)	$615/lin.ft. for busy 2-lane road with 15 ft embankment	None	Road or lane closure; run-off and environmental degradation; stream flow bypass necessary

Sources: FLH Bid History from various departments, 1997 to present; USDA Forest Service Report on Trenchless Technologies; Piehl, 2005; Caltrans Supplement to FHWA Practices Manual Bulletin No. 83-01, 2006; Central FLH Culvert Pipe Liner Guide, 2005.

Notes: Expenses related to road closures and economic disruptions are not included in cost estimates presented here

Level 1 Performance Problems - Causes and Fixes

Use this matrix to identify appropriate fixes for Level 1 performance problems identified in the assessment.

Problem	Indicators Seen In Field	Potential Causes	Recommended Fix
Maintenance/Clearing Needed	Debris or vegetation blocks 1/3 or more of rise at inlet	Buildup of debris or vegetation from one or more flow events or ongoing flow conditions	Clearing by client maintenance forces
Previous Overtopping	Drift on guardrail	Debris or vegetation blockage	Clearing by client maintenance forces, repair of any embankment damage
	Erosion on downstream side of embankment	Inlet Failure	Repair inlet as needed, repair any embankment damage as detailed below for inlet failure problem
	Loss of pavement, especially along downstream edge	Sediment blockage through barrel < 1/3 of rise	Clearing by client maintenance forces, repair of any embankment damage
		Local sediment blockage @ inlet or outlet 1/3 to 3/4 rise	
Frequent Overtopping	Known maintenance history, report from client	Causes listed above for "previous overtopping"	See corresponding recommended fix above
		Undersized culvert (if potential causes listed above are absent)	Perform hydrologic/hydraulic analysis to determine appropriate culvert size, replace if necessary
Inlet Failure	Mitered inlet edge curled inward	Inadequate edge strength to resist soil pressure of embankment	Repair inlet as needed (unless culvert is to be replaced), add lateral support via headwall or slope paving
	Inlet barrel raised above streambed	Unbalanced bouyancy uplift	Repair inlet as needed (unless culvert is to be replaced), add headwall for counterweight
Local Scour at Outlet	Undermined culvert, apron, flared end section, or embankment slope	Scour protection needed but never provided	Repair damage, provide appropriate scour protection
		Scour protection provided but failed	Repair or replace scour protection, see Decision Flowchart, Page 7, Appurtenances
Poor Channel Alignment	Damage to embankment and/or apron, wingwalls, or flared end section, and barrel axis skewed to channel by 45 degrees or more	Scour caused by poor angle of attack not adequatly mitigated	Repair damage as needed, provide scour protection covering areas previously damaged, including embankment adjacent to end treatment and channel banks in vicinity of culvert/embankment

Level 2 Performance and Other Problems - Disciplines Required for Investigation

Use this table to determine the appropriate discipline(s) needed to conduct Level 2 investigations where needed.

Problem	Indicators Seen in Field	Disciplines Required for Investigation
Embankment Piping	Settlement or holes in roadway or embankment with no significant culvert barrel condition problems	Geotechnical
Channel Degradation	Perched inlet and/or outlet with adjacent channel banks vertical or unstable (sloughing)	Hydraulics
Headcut	Unstable channel drop of 2 feet height or more within sight of culvert	Hydraulics
Embankment Slope Instability	Failure of upstream embankment with channel skew angle less than 45 degrees to barrel axis or failure of downstream embankment not explained by overtopping or outlet scour	Geotechnical
Sediment Blockage and Channel Aggradation	Local sediment blockage > 3/4 rise at inlet or outlet	Hydraulics
	Full barrel length blocked 1/3 or more with sediment and culvert not designed intentionally for AOP	
No Access	Condition cannot be adequately assess by an end-only Level 1 inspection. Access is prevented by factors not remedied by routine maintenance.	Underwater or Climbing Inspector or other specialist and equipment
Aggressive Abrasion, Corrosion and/or Chemical Environment*	Poor or Critical condition reached in 5 years or less	Materials, Hydraulics, Geotechnical
AOP Culvert with Poor or Critical Condition Rating or with Performance Problem	Any action required due to performance problems or condition ratings	Environmental Resource Specialists and Hydraulics
Historical culvert with Poor or Critical Condition Rating or with a Performance Problem	Any action required due to performance problems or condition ratings	Cultural Resource Specialists and Hydraulics
Structural Cracking	Significant cracking that is suspected to compromise the structural integrity of the culvert and diminish load carrying capacity	Structural
Open-bottom culvert*	More than 10 feet of side of footing exposed. Any open-bottom culvert requiring action due to Poor or Critical condition ratings	Hydraulics, Geotechnical

* Item also noted in the condition assessment tables