American Concrete Pipe Association | RIGID RUGGED RESILIENT | concretepipe.org

EVERY DAY MATTERS

Reinforced Concrete Pipe

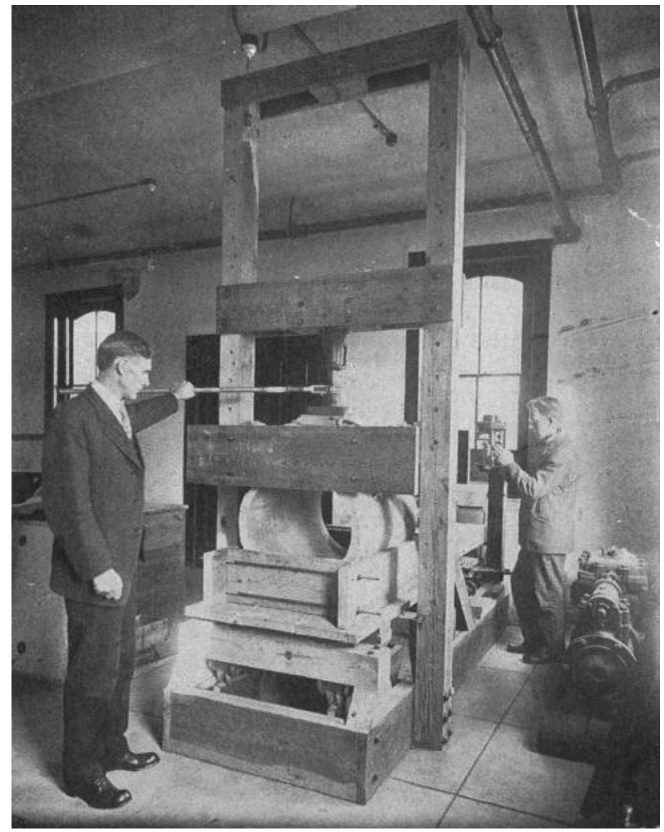
How to Assess the Transition from Indirect to Direct Design Methods in Deep Cover Installations

Adam Braun, P.Eng.
Winnipeg, Manitoba
Canada

AECOM

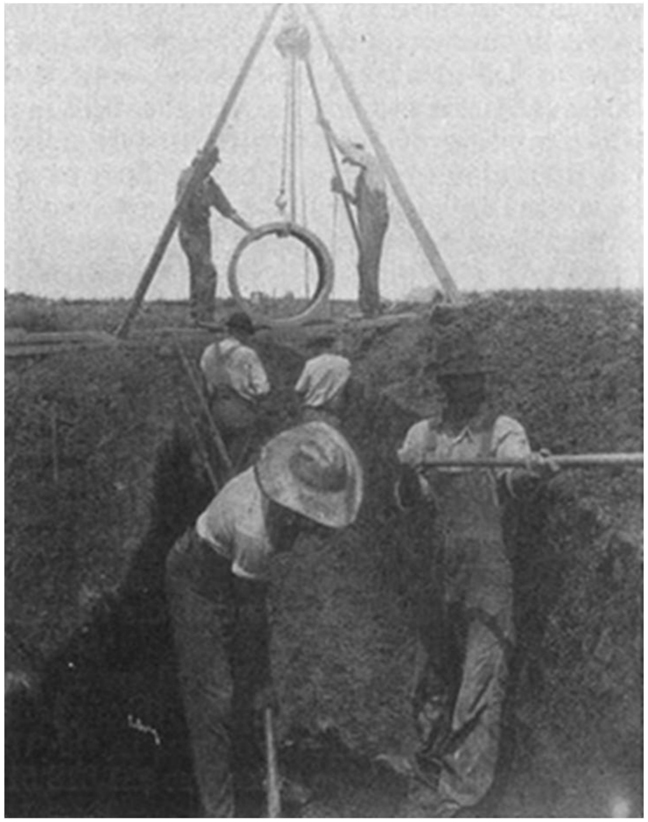
- Introduction, Background, and History
- Indirect Design
- SIDD Installations and Direct Design
- Transition from Indirect to Direct Design
- Conclusion

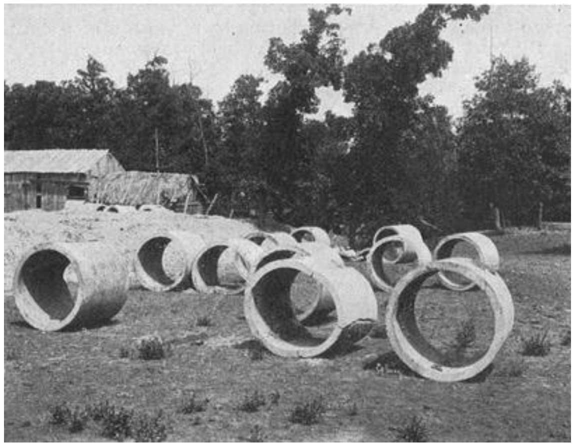
Introduction, Background & History



Introduction

- Reinforced Concrete Pipe (RCP)
- First produced in 1896 in France
- Brought to North America in 1905





Introduction

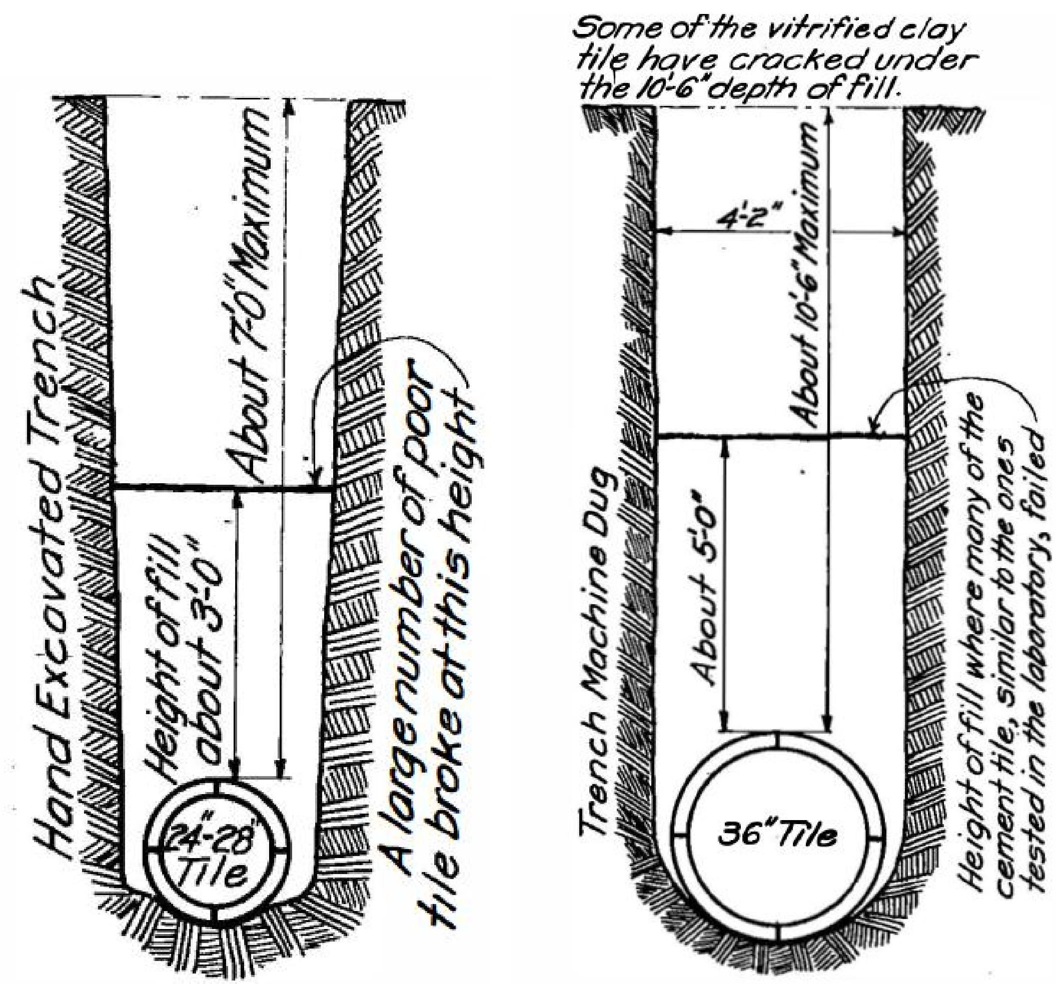
- Indirect Design (Marston/Spangler Analysis)
  - Developed in the 1920's and 30's
  - Empirically derived
  - Excellent performance record in low to moderate soil covers
- Direct Design (Heger/Selig)
  - Developed in the 1970's and 80's
  - Reinforced concrete design theory
  - Limit states design principals
  - Applicable for large diameter and high external load conditions

While direct design has been formally adopted by industry it does not see widespread use

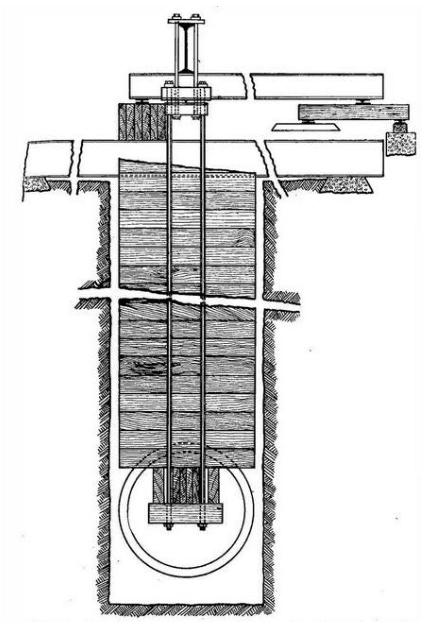
Iowa Experiment Station

- Anson Marston began research into the behavior of buried rigid pipe in 1910
- Born out of the increased use of clay and non reinforced concrete pipe in sizes up to 36” as both drain tile and sewer pipe
- The “large diameter” pipe was prone to failure shortly after installation
- Began with investigation into failures

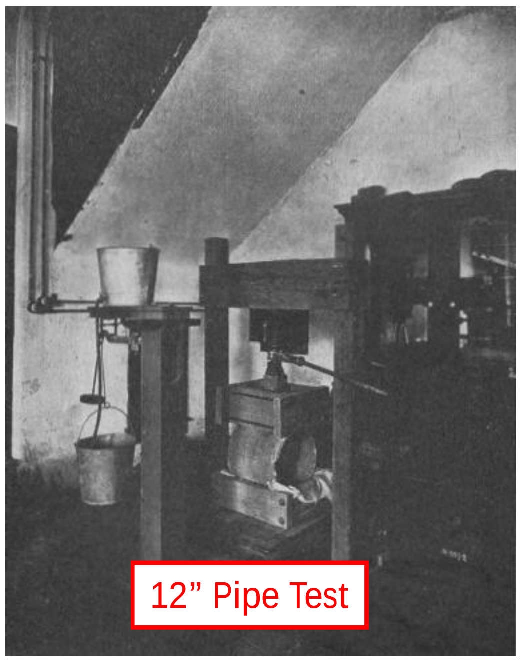
At the time there was no quantifiable design method for buried pipe!



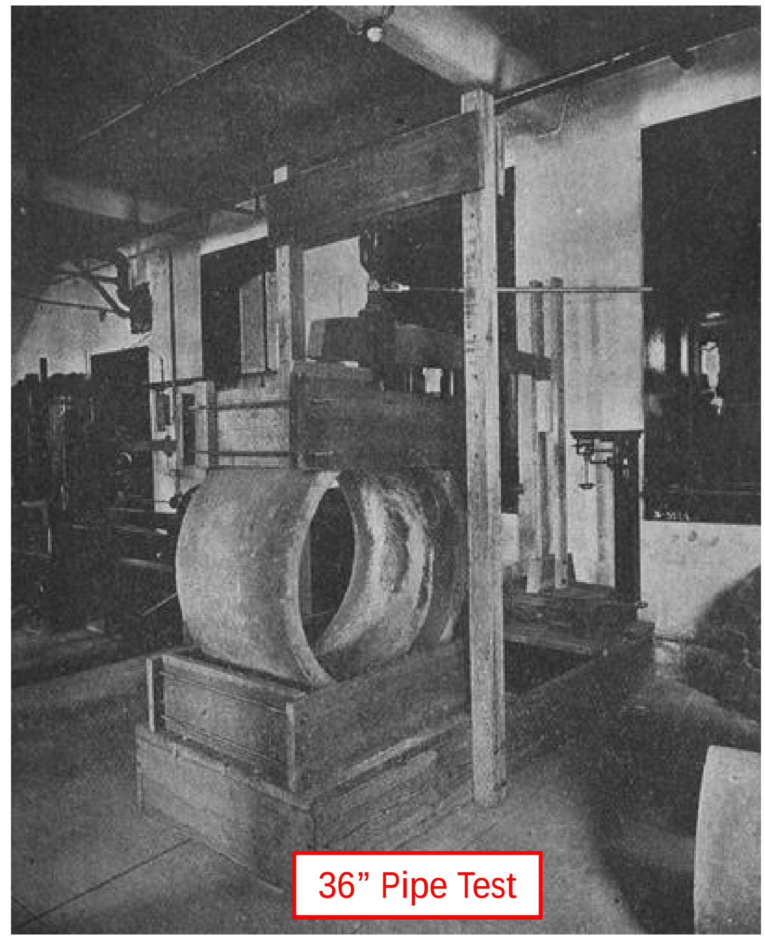
Original Soil Load and Pipe Strength Experiments



Evaluating Trench Loads



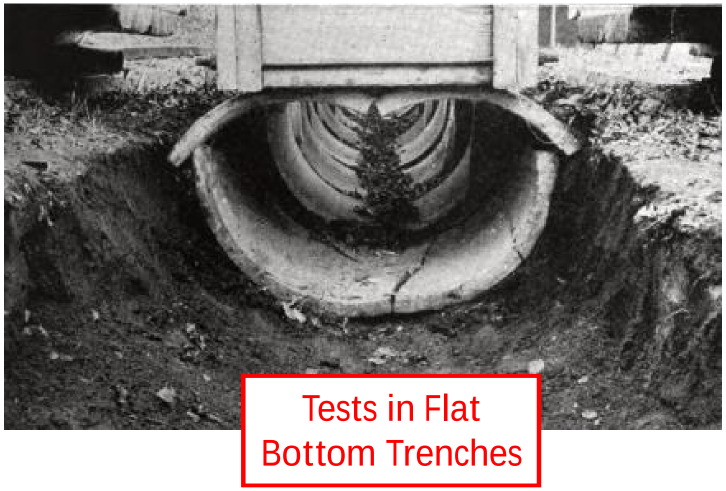
12” Pipe Test

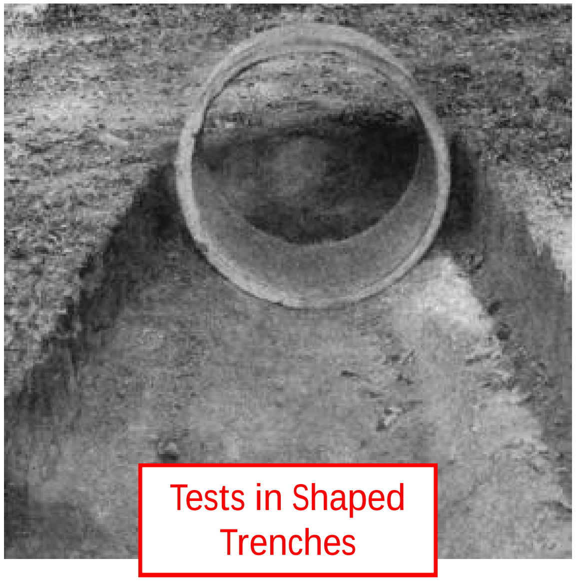


36” Pipe Test

Original Soil Load and Pipe Strength Experiments

- Testing of pipe up to 42” diameter
- Homebuilt sand bedding testing machines
- Evaluation of test results to actual supporting strength for various installation types





Evaluation of Testing Methods

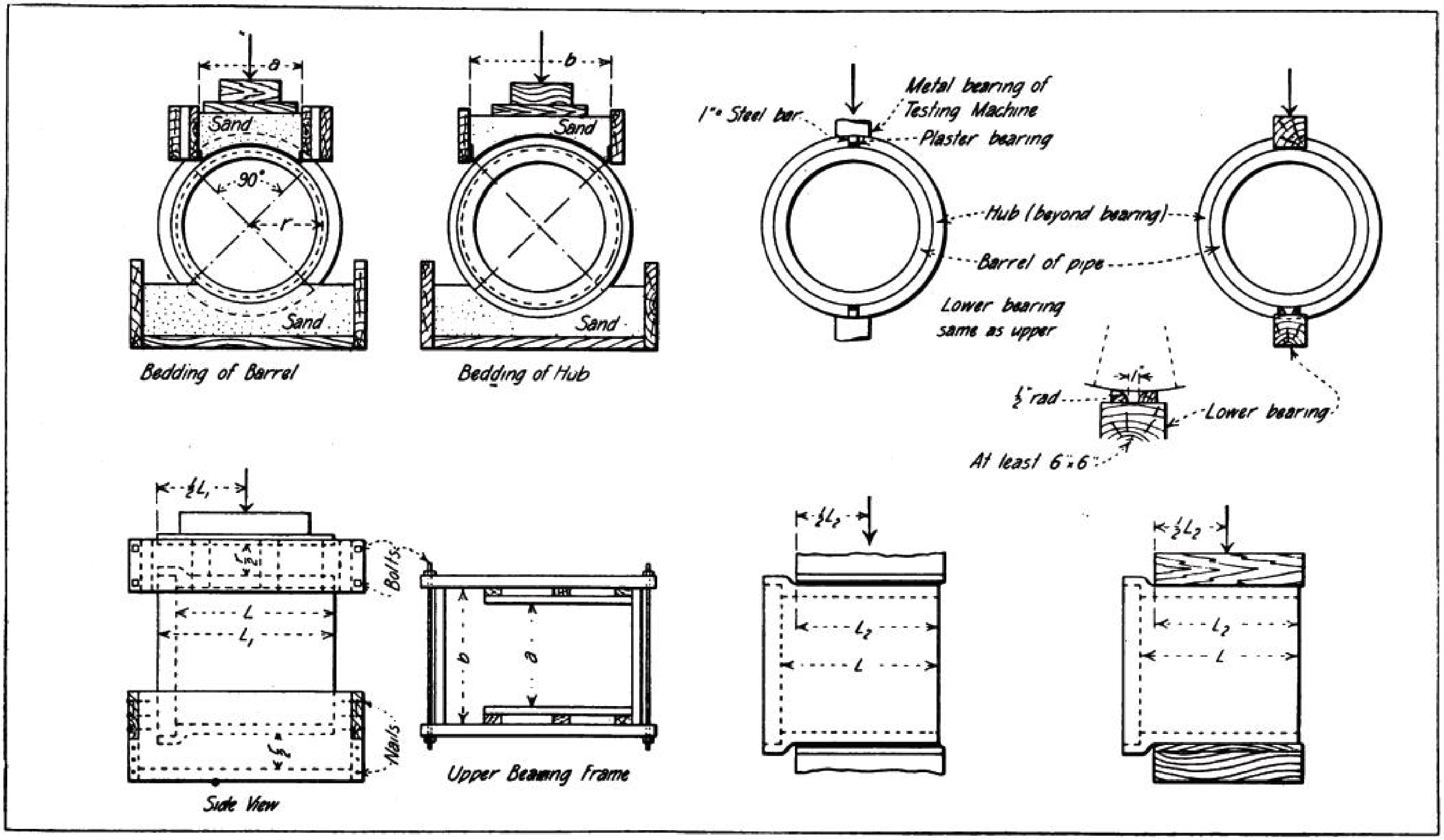
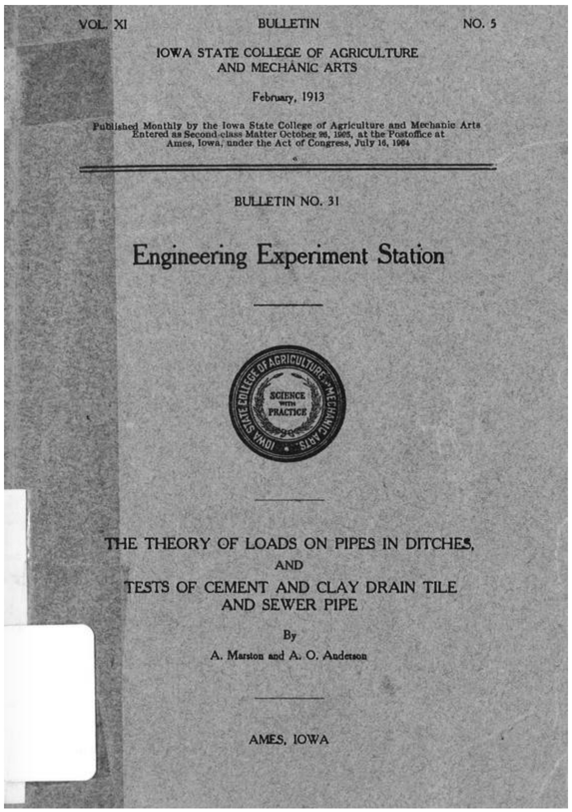


Fig. 16. "Sand" bearings Fig. 17. "Two-point" bearings Fig. 18. "Three-point" bearnigs

Bearings recommended for use in tests of the "ordinary supporting strength" of sewer pipe

The Theory of Loads on Pipes in Ditches and Tests of Cement and Clay Drain Tile and Sewer Pipe



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Ames, Iowa, under the Act of Congress, July 16, 1904

BULLETIN NO. 31

Engineering Experiment Station

IOWA STATE COLLEGE OF AGRICULTURE AND MECHANIC ARTS
SCIENCE WITH PRACTICE

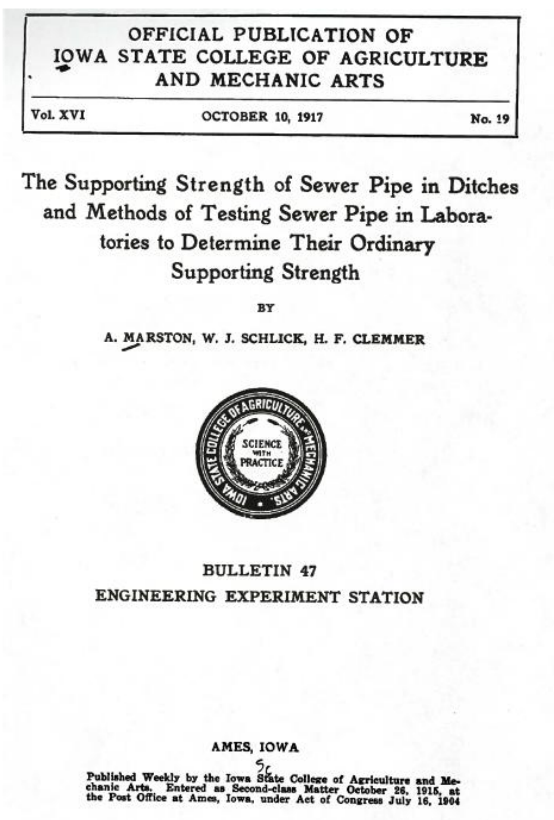
THE THEORY OF LOADS ON PIPES IN DITCHES,
AND
TESTS OF CEMENT AND CLAY DRAIN TILE
AND SEWER PIPE

By
A. Marston and A. O. Anderson

AMES, IOWA

- Published in 1913 by the Iowa State College of Agriculture and Mechanical Arts
- Authors:
  - Anson Marston
  - A. O. Anderson
- New theories for calculating soil loads on buried pipes in narrow trenches

The Supportive Strength of Sewer Pipe in Ditches and Methods of Testing Sewer Pipe in Laboratories to Determine Their Ordinary Supportive Strength



OFFICIAL PUBLICATION OF
IOWA STATE COLLEGE OF AGRICULTURE
AND MECHANIC ARTS

Vol. XVI OCTOBER 10, 1917 No. 19

The Supporting Strength of Sewer Pipe in Ditches and Methods of Testing Sewer Pipe in Laboratories to Determine Their Ordinary Supporting Strength

BY

A. MARSTON, W. J. SCHLICK, H. F. CLEMMER

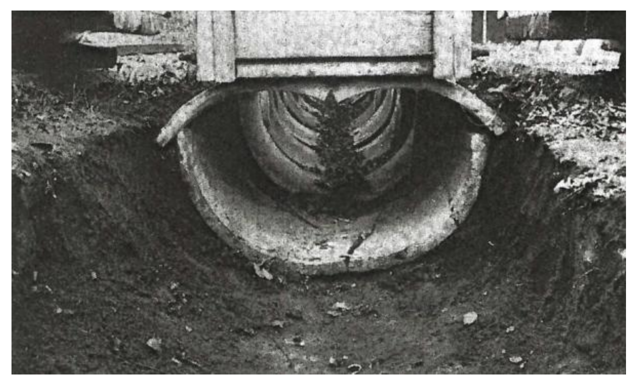
IOWA STATE COLLEGE OF AGRICULTURE & MECHANIC ARTS
SCIENCE WITH PRACTICE

BULLETIN 47
ENGINEERING EXPERIMENT STATION

AMES, IOWA

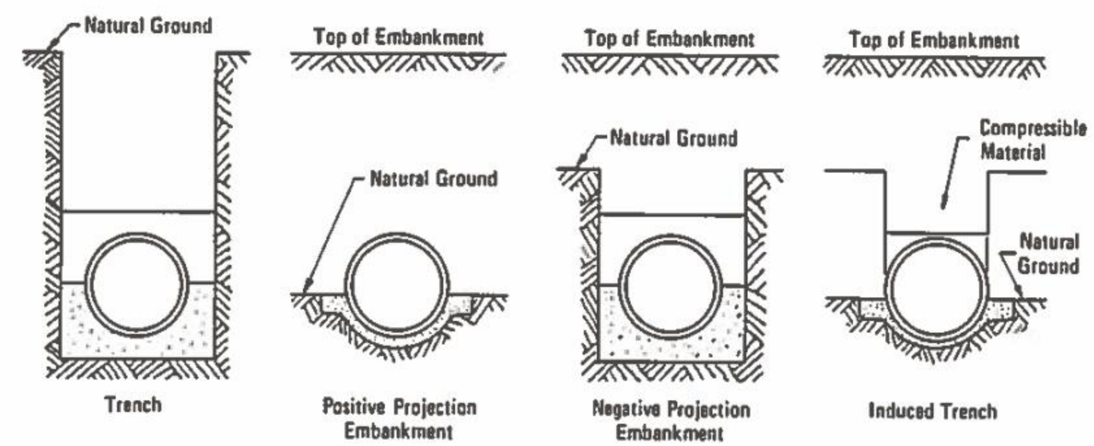
Published Weekly by the Iowa State College of Agriculture and Mechanic Arts. Entered as Second-class Matter October 26, 1915, at the Post Office at Ames, Iowa, under Act of Congress July 16, 1904

- Published in 1917 by the Iowa State College of Agriculture and Mechanical Arts
- New theories for quantifying the external load capacity of buried rigid pipe
- Authors:
  - Anson Marston
  - W. J. Schilick
  - H. F. Clemmer

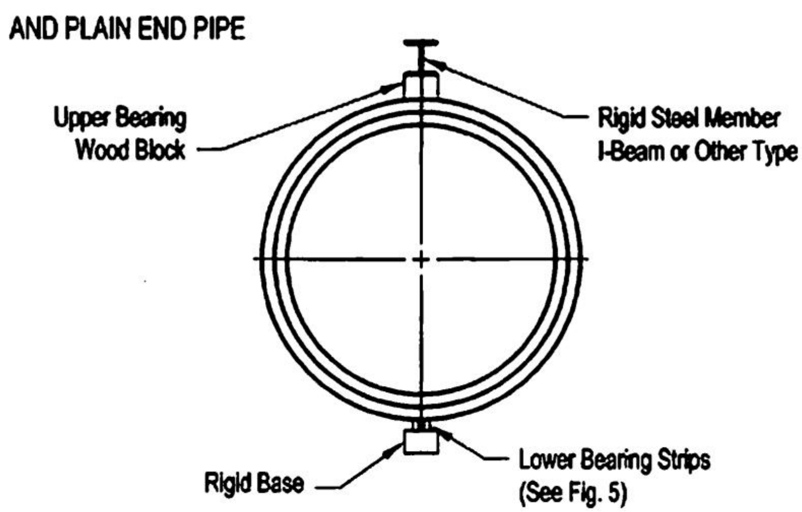


Continued Research…

- Further development was undertaken in the 1920’s and 30’s by:
  - W. J. Schilick
  - M. G. Spangler
- Resulted in numerous papers on an ever expanding knowledge of soil loads and pipe strengths
- Developed calculations for determining earth loads from embankment (projection) and tunnel installations
- Load calculations were all empirically derived from experiments undertaken at the Iowa Experiment Station



Indirect Design



Indirect Design

- Matches estimated trench loads to the estimated supporting strength of the installed pipe
- Installed pipe strengths estimated through the use of empirically derived factors
- Pipe strengths assessed using three edge bearing (3EB) tests

TABLE 5 Design Requirements for Class V Reinforced Concrete Pipe[A]

NOTE 1—See Section 5 for basis of acceptance specified by the owner.

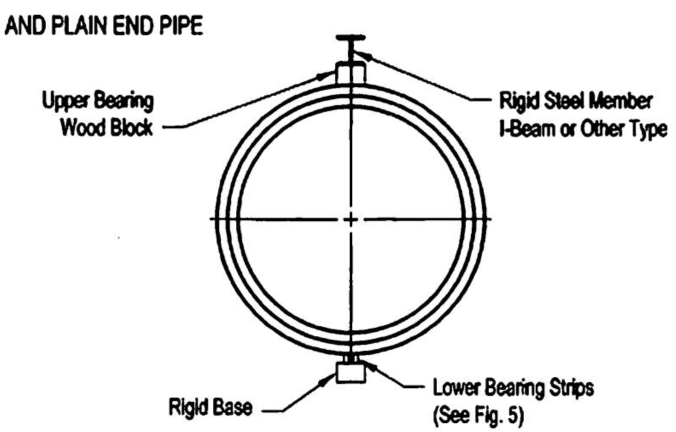
The strength test requirements in pounds-force per linear foot of pipe under the three-edge-bearing method shall be either the D-load (test load expressed in pounds-force per linear foot per foot of diameter) to produce a 0.01-in. crack, or the D-loads to produce the 0.01-in. crack and the ultimate load as specified below, multiplied by the internal diameter of the pipe in feet.

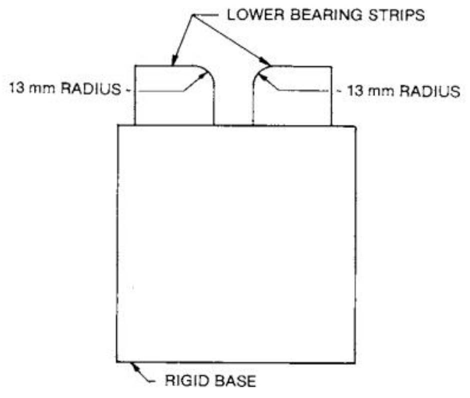
D-load to produce a 0.01-in. crack	3000
D-load to produce the ultimate load	3750

Internal Designated Diameter, in.	Reinforcement, in.²/linear ft of pipe wall											
	Wall A				Wall B				Wall C			
	Concrete Strength, 6000 psi				Concrete Strength, 6000 psi				Concrete Strength, 6000 psi			
	Wall Thickness, in.	Circular Reinforcement[B]		Elliptical Reinforcement[C]	Wall Thickness, in.	Circular Reinforcement[B]		Elliptical Reinforcement[C]	Wall Thickness, in.	Circular Reinforcement[B]		Elliptical Reinforcement[C]
		Inner Cage	Outer Cage			Inner Cage	Outer Cage			Inner Cage	Outer Cage	
12	[A]	...	...	...	2	0.10	...	...	2¾	0.07[D]	...	...
15	[A]	...	...	...	2¼	0.14	...	...	3	0.07[D]	...	...
18	[A]	...	...	...	2½	0.19	...	0.16	3¼	0.10	...	...
21	[A]	...	...	...	2¾	0.24	...	0.21	3½	0.10	...	...
24	[A]	...	...	...	3	0.30	...	0.24	3¾	0.12	0.07	0.12
27	[A]	...	...	...	3¼	0.38	0.23	0.42	4	0.14	0.08	0.16
30	[A]	...	...	...	3½	0.41	0.24	0.45	4¼	0.18	0.11	0.20
33	[A]	...	...	...	3¾	0.45	0.27	0.51	4½	0.23	0.14	0.24
36	[A]	...	...	...	4	0.50	0.30	0.56	4¾	0.27	0.16	0.30
42	[A]	...	...	...	4½	0.60	0.36	0.67	5¼	0.36	0.21	0.40
48	[A]	...	...	...	5	0.73	0.44	0.81	5¾	0.47	0.27	0.52
54	[A]	...	...	...	[A]	......	...	...	6¼	0.58	0.35	0.64
60	[A]	...	...	...	[A]	...	...	...	6¾	0.70	0.42	0.78
66	[A]	...	...	...	[A]	...	...	...	7¼	0.84	0.50	0.93
72	[A]	...	...	...	[A]	......	...	...	7¾	0.99	0.59	1.10
78	[A]	...	...	...	[A]	...	...	...	[A]	...	...	...
84	[A]	...	...	...	[A]	...	...	...	[A]	...	...	...
90	[A]	...	...	...	[A]	...	...	...	[A]	...	...	...
96	[A]	...	...	...	[A]	...	...	...	[A]	...	...	...
102	[A]	...	...	...	[A]	...	...	...	[A]	...	...	...
108	[A]	...	...	...	[A]	...	...	...	[A]	...	...	...
114	[A]	...	...	...	[A]	...	...	...	[A]	...	...	...
120	[A]	...	...	...	[A]	...	...	...	[A]	...	...	...
126	[A]	...	...	...	[A]	...	...	...	[A]	...	...	...
132	[A]	...	...	...	[A]	...	...	...	[A]	...	...	...
138	[A]	...	...	...	[A]	...	...	...	[A]	...	...	...
144	[A]	...	...	...	[A]	...	...	...	[A]	...	...	...

Three Edge Bearing Tests

- Standards:
  - ASTM C497 - Standard Test Methods for Concrete Pipe, Manhole Sections, or Tile
  - CSA A257
- Quantifiable means of determining a pipe ability to support externally applied loads





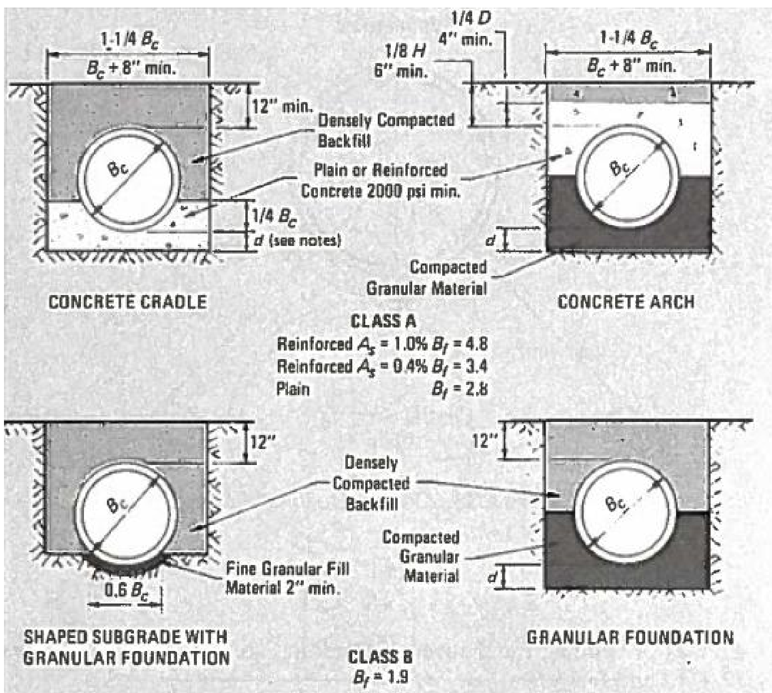
Three Edge Bearing Tests

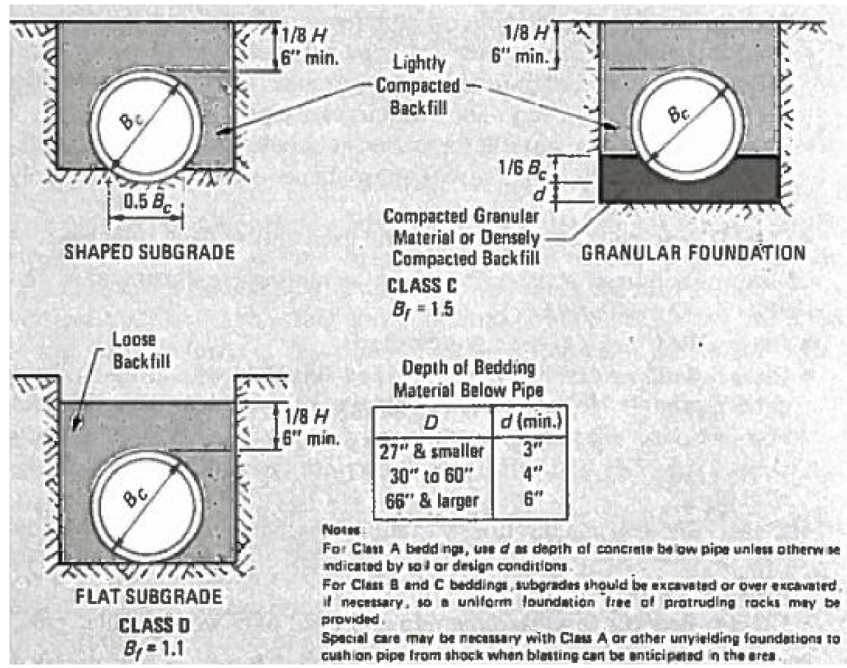
- RCP is typically tested with the intent of determining the following loads:
  - Hairline Crack
  - Service Cracking (0.01” or 0.3 mm)
  - Ultimate Failure
- Typical QA/QC procedures only require testing up to servicing cracking limit with the rare test taken to ultimate failure
- It should be noted that standard three edge bearing tests to do not check for diagonal tension (shear) or radial tension failure modes.
- Both are governing failure modes in high soil cover conditions.

Traditional Installation Types and Bedding Factors

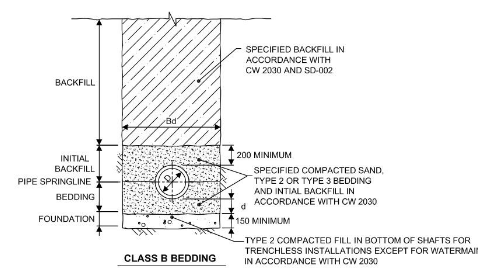
- Bedding types developed to reflect pipe installation methods at the beginning of the 1900's
- Reflect installation efforts involving hand vs. machine excavation
- Bedding factors were developed for each installation type reflect the increase in load a pipe can support when installed vs. in the three edge bearing test
- The bedding factor each installation type reflects the level of load distribution provided
- Better soil support equals a higher bedding factor!

Traditional Installation Types and Bedding Factors





D	d (min.)
27" & smaller	3"
30" to 60"	4"
66" & larger	6"



Indirect Design Method

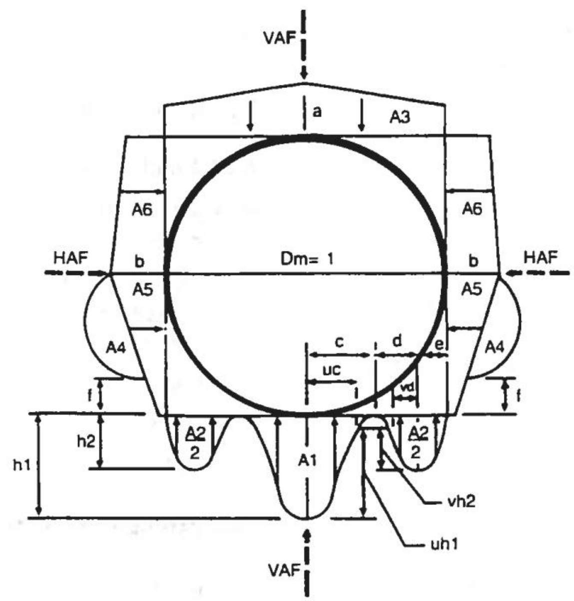
- Calculate live and dead loads
- Determine a bedding factor
- Determine the equivalent three edge bearing load (divide the soil load by the bedding factor)
- Convert to equivalent D-Load (Divide by the diameter of the pipe)
- Select appropriate pipe from the ASTM or CSA specification or specify required load

ASTM C76 Pipe Class	Service Cracking D-Load (N/m/mm)	Ultimate Failure D-Load (N/m/mm)
Class I	40	60
Class II	50	75
Class III	65	100
Class IV	100	150
Class V	140	175

Indirect Design Method

- Reinforcement requirements are stipulated in ASTM C76 or CSA A257
- Empirically derived in order to meet required D-Loads
- Single factor of safety applied against ultimate failure, ranging from 1.25 and 1.5
- No differentiation between live and dead loads and their respective levels of uncertainty
- Adequate for low to moderate soil covers consistent with those used to develop the empirical design method

SIDD Installations and Direct Design

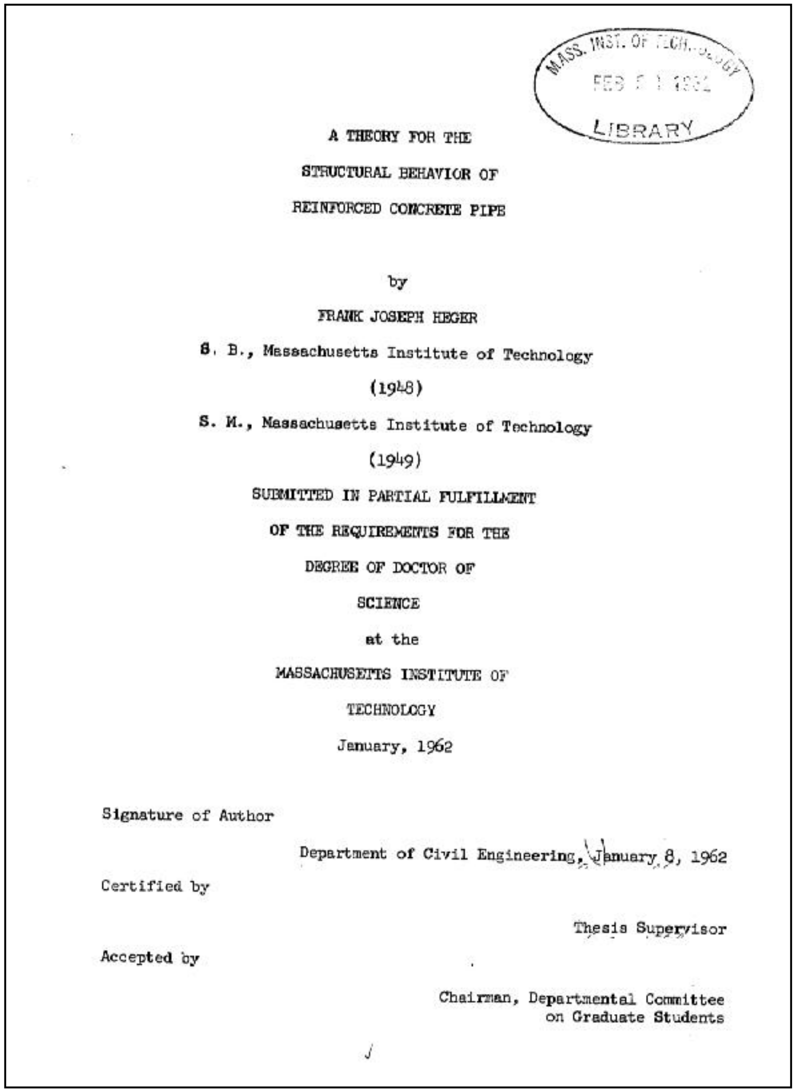


New Design Approach

- American Concrete Pipe Association (ACPA) undertook a long term research project in the 1970's and 80's to develop a new design approach for reinforced concrete pipe
- Dr. Frank Heger was engaged to develop this new design method based on his knowledge of reinforced concrete design
- Continuation of Heger's post graduate work at MIT
- Dr. Ernest Selig was engaged to provided geotechnical expertise in development of the pipe-soil interaction models
- Heger's other work included…

New Design Theory

- Heger's 1962 PhD thesis "A Theory for the Structural Behavior of Reinforced Concrete Pipe" strove to develop a rational procedure for predicting the structural behavior of reinforced concrete pipe
- Adapted reinforced concrete beam theory to the circular pipe wall



A THEORY FOR THE
STRUCTURAL BEHAVIOR OF
REINFORCED CONCRETE PIPE

by

FRANK JOSEPH HEGER

S. B., Massachusetts Institute of Technology
(1948)

S. M., Massachusetts Institute of Technology
(1949)

SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE
DEGREE OF DOCTOR OF
SCIENCE
at the
MASSACHUSETTS INSTITUTE OF
TECHNOLOGY
January, 1962

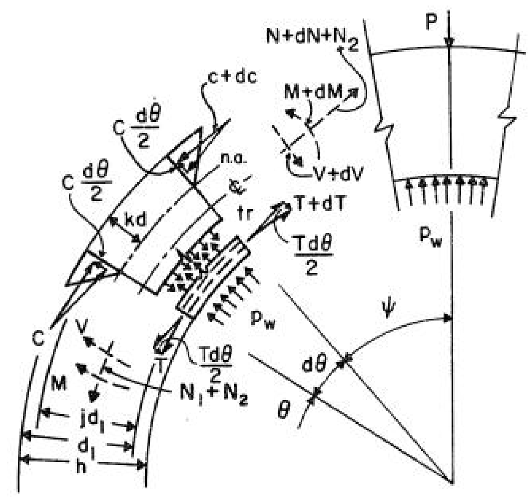
Signature of Author
Department of Civil Engineering, January 8, 1962

Certified by
Thesis Supervisor

Accepted by
Chairman, Departmental Committee
on Graduate Students

New Design Theory

- Proposed design procedures considered the following:
  - Flexural strength
  - Diagonal tension (shear) capacity
  - Predicting and limiting in service crack widths
  - Use of stirrups in controlling diagonal tension
  - Combined internal and external loading conditions
- Assessed the development of internal wall forces under test (3EB) and in service conditions

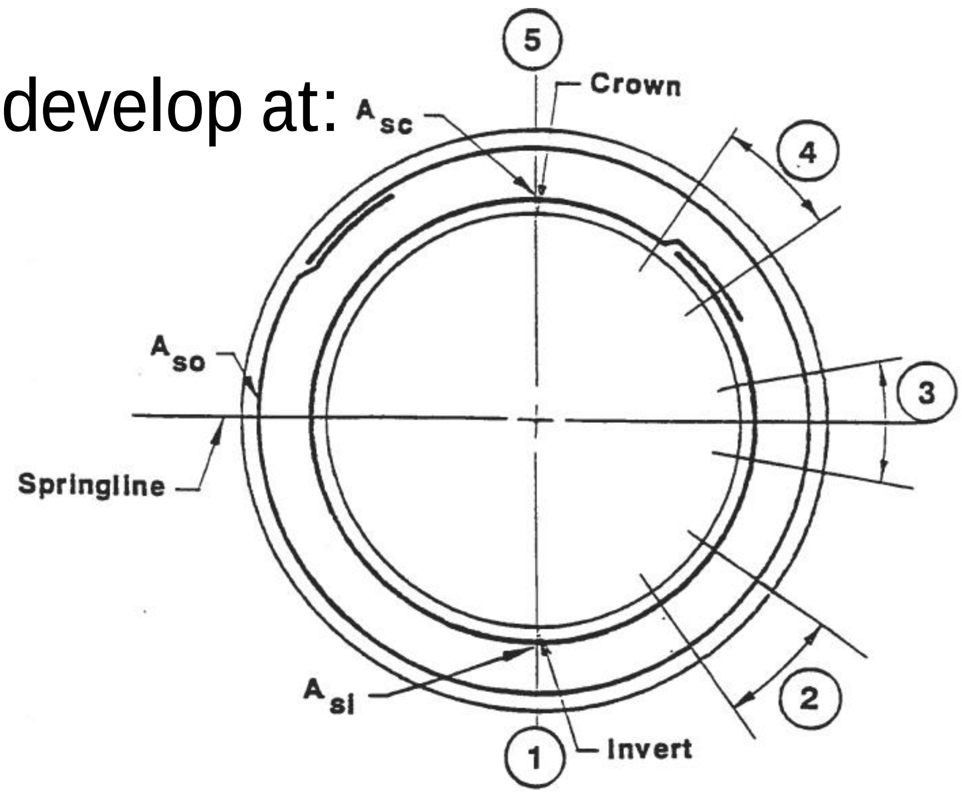


RADIAL TENSION STRESS IN PIPE WALL UNDER COMBINED THREE-EDGE BEARING LOAD AND INTERNAL PRESSURE

(Heger 1962)

Imparted Wall Forces

- Max bending moments develop at:
  - Obvert
  - Invert
  - Springline
- Max wall thrust:
  - Springline
- Max diagonal tension:
  - ≈12° to 13° from invert



Flexure Design Locations:

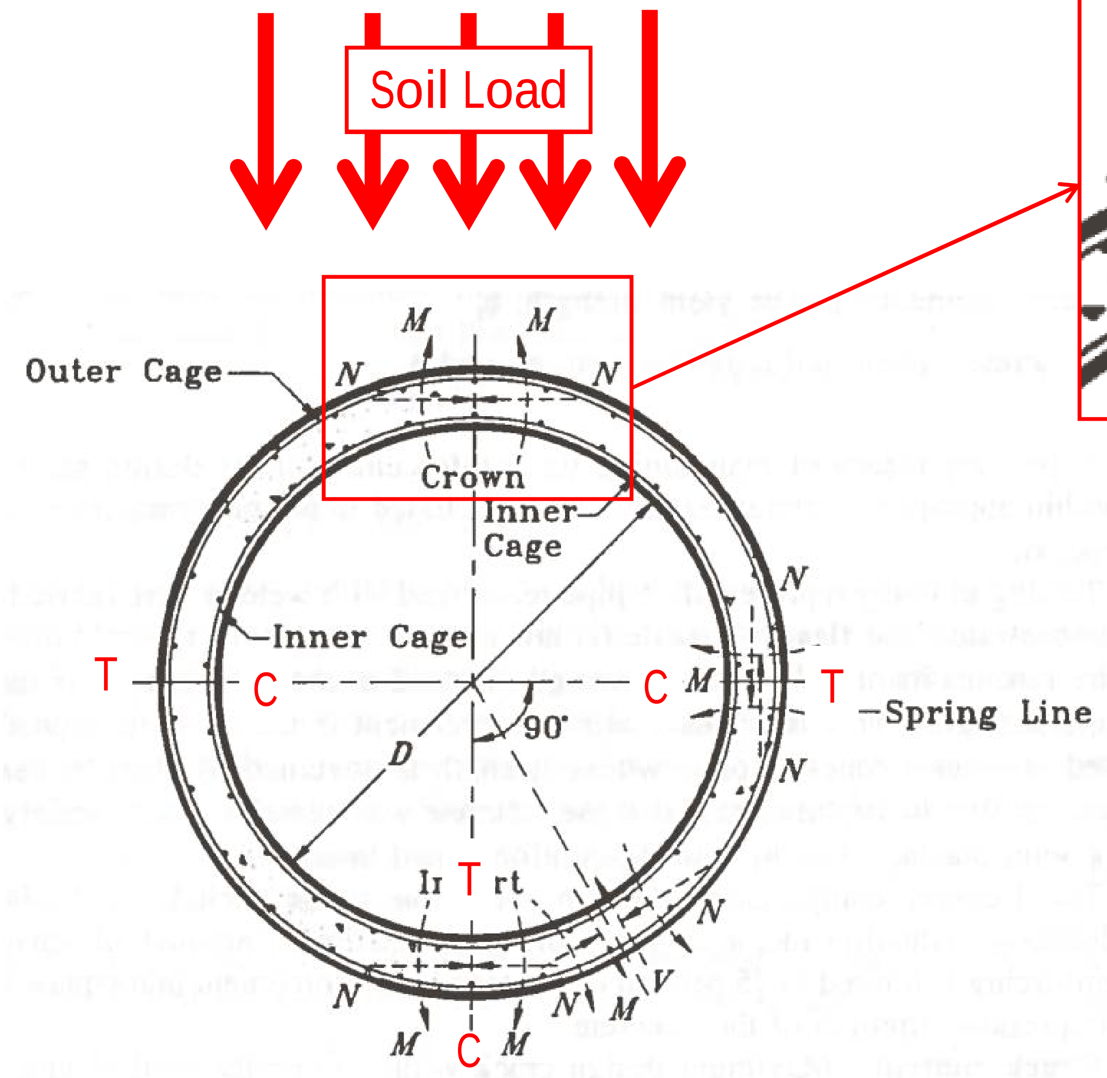
1,5 Maximum Positive Moment Locations at Invert and Crown.

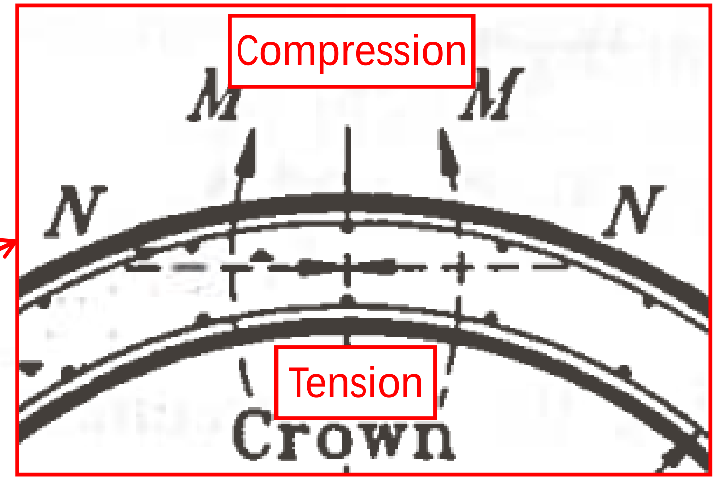
3 Maximum Negative Moment Location Near Springline.

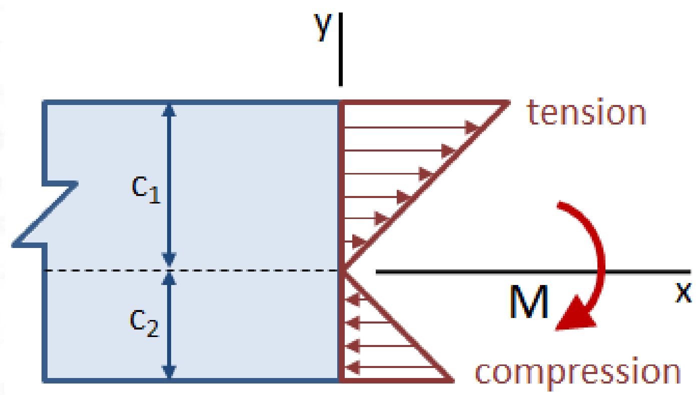
Shear Design Locations:

2,4 Locations Near Invert and Crown Where Mnu/(Vud) = 3.0

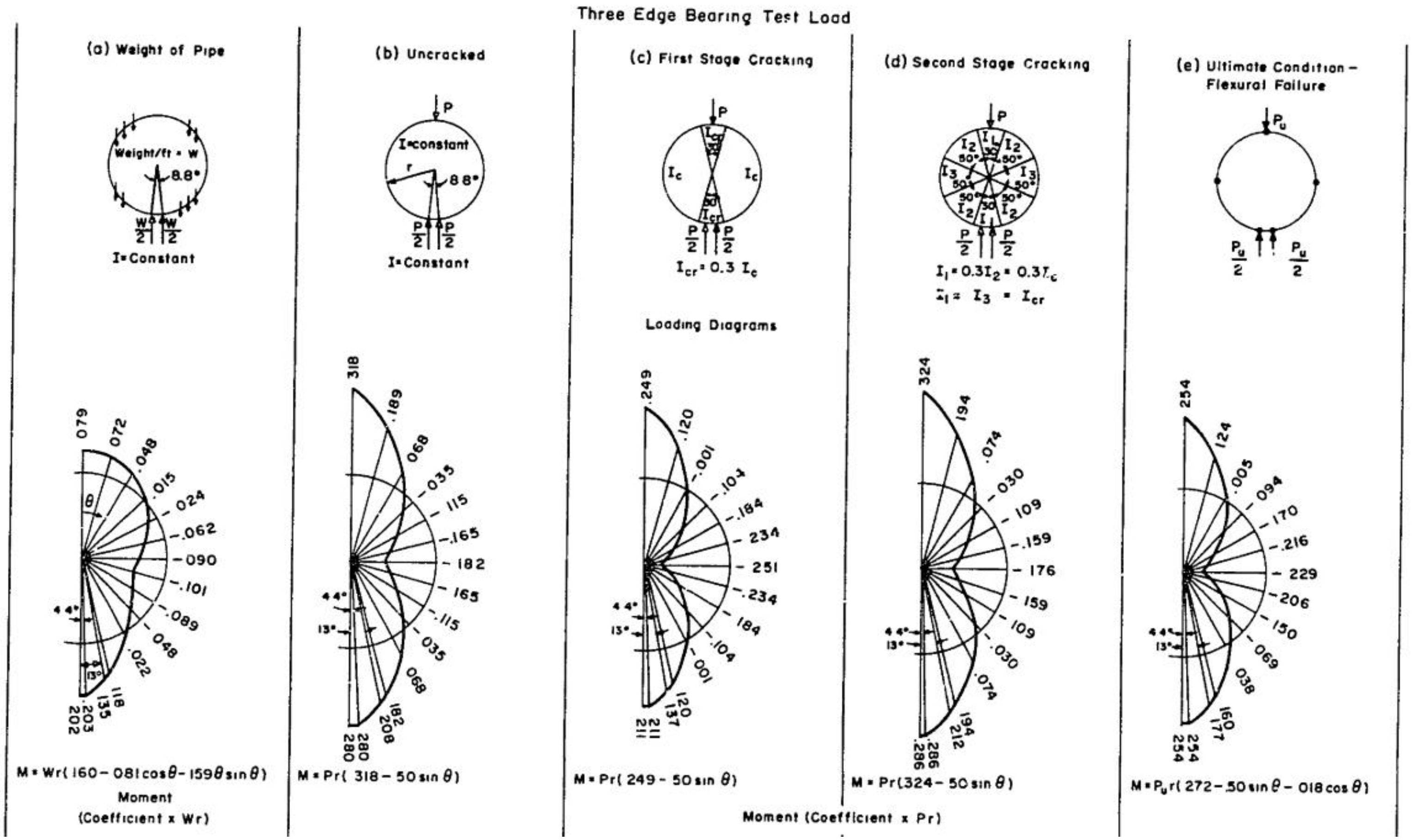
Bending Moments







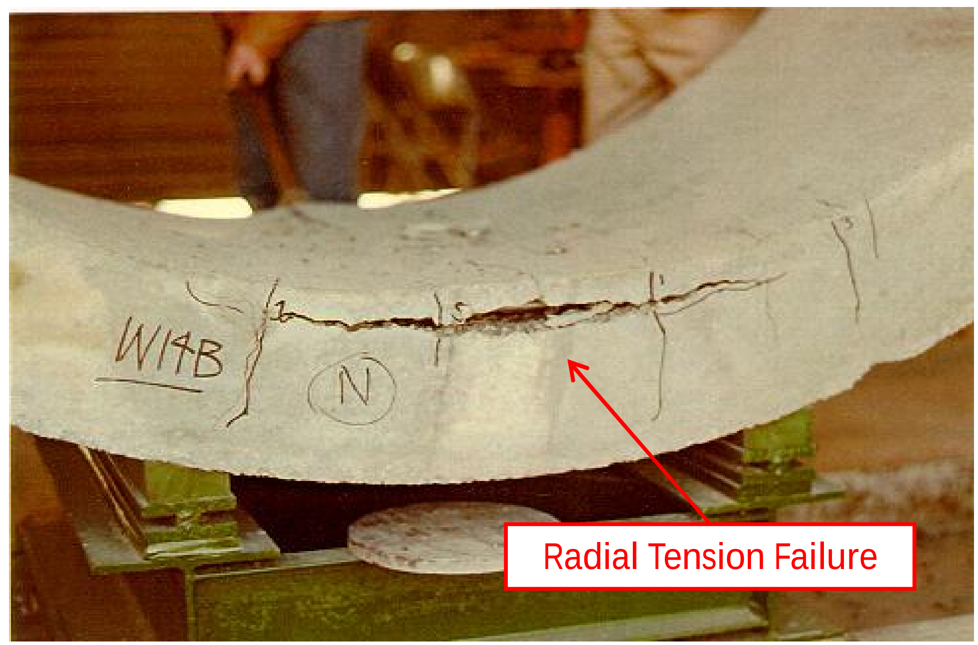
Development of Bending Moments during 3EB Test



(Heger 1962)

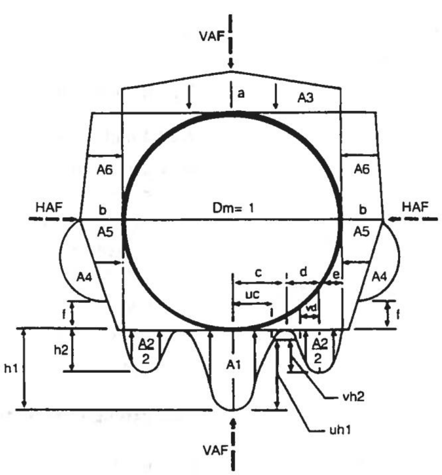
Diagonal and Radial Tension

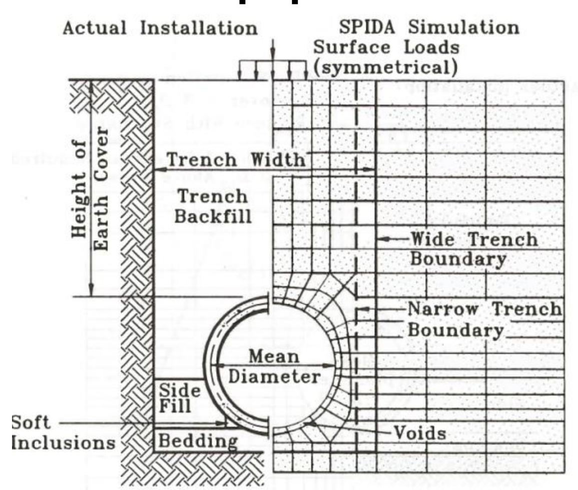
- Radial Tension Failure:
  - Cause by tension forces within the radial reinforcement
  - These tension forces act to straighten out curved steel, causing it to pull away from the pipe wall

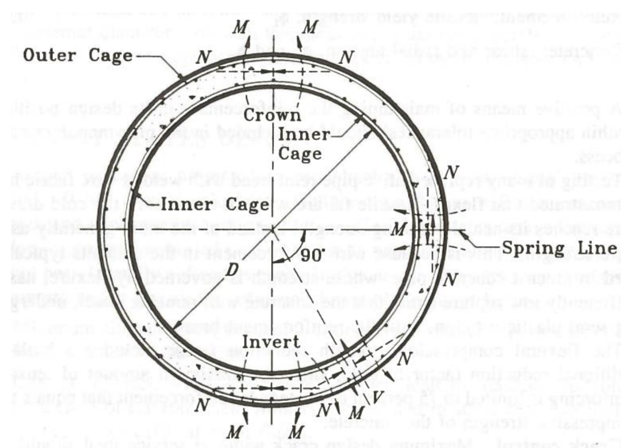


Soil Pressures and Wall Forces

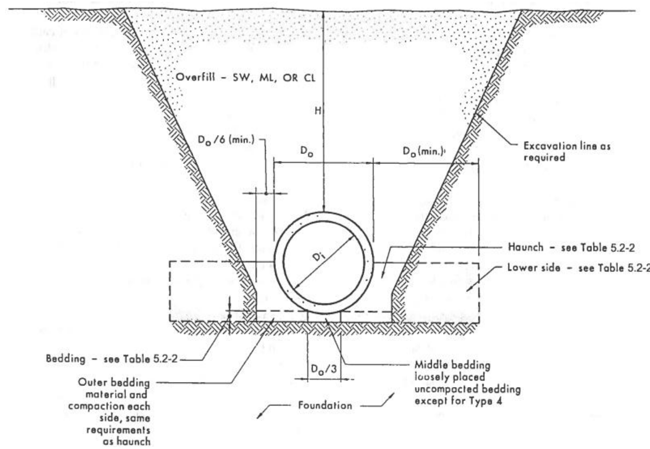
- The interaction between buried pipe, the embedment material, and native soils is complex and dependent on many factors
- Heger and Selig developed the computerized finite element program SPIDA (Soil-Pipe Interaction Design and Analysis) to determine the distribution of soil pressures around the pipe and wall forces developed
- This lead to the development of four new installation types to reflect modern pipe installation techniques…







Standard Installations Direct Design (SIDD)



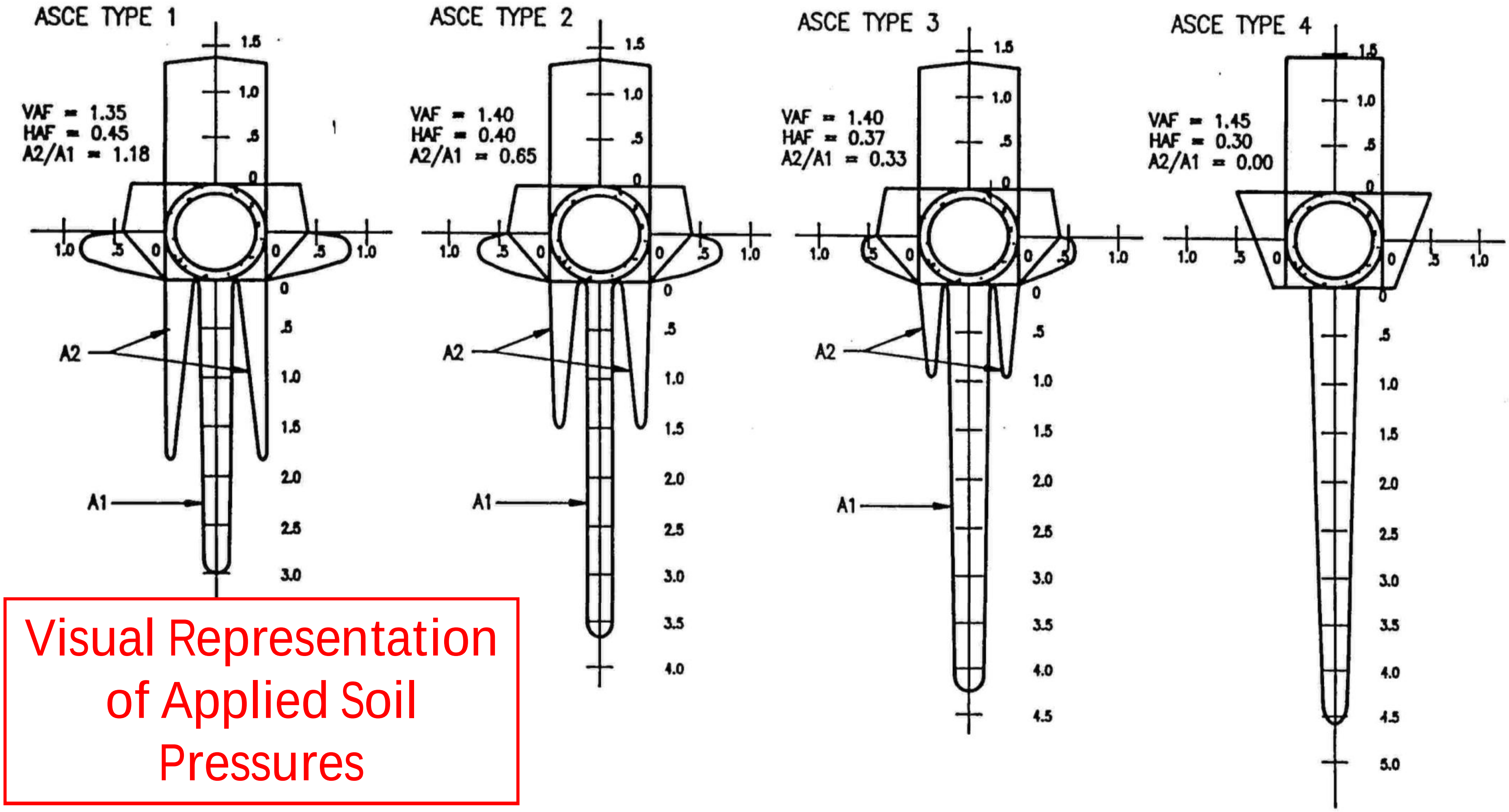
Quantitative vs. Qualitative Installation Procedure

Most Intensive Installation Requirements

Least Intensive Installation Requirements

Installation Type	Bedding Thickness	Haunch and Outer Bedding	Lower Side
Type 1	D_o/24 minimum, not less than 3 in. (75 mm). If rock foundation, use D_o/12 minimum, not less than 6 in. (150 mm).	95% SW	90% SW, 95% ML, or 100% CL
Type 2	D_o/24 minimum, not less than 3 in. (75 mm). If rock foundation, use D_o/12 minimum, not less than 6 in. (150 mm).	90% SW or 95% ML	85% SW, 90% ML, or 95% CL
Type 3	D_o/24 minimum, not less than 3 in. (75 mm). If rock foundation, use D_o/12 minimum, not less than 6 in. (150 mm).	85% SW, 90% ML, or 95% CL	85% SW, 90% ML, or 95% CL
Type 4	No bedding required, except if rock foundation, use D_o/12 minimum, not less than 6 in. (150 mm).	No compaction required, except if CL, use 85% CL	No compaction required, except if CL, use 85% CL

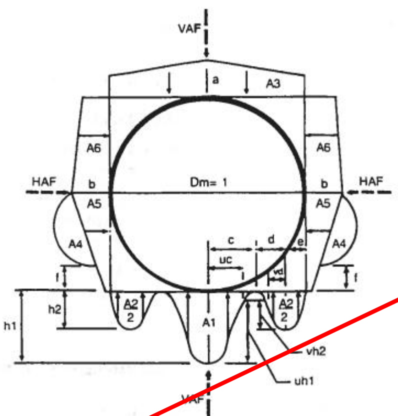
Standard Installations Direct Design (SIDD)



Visual Representation of Applied Soil Pressures

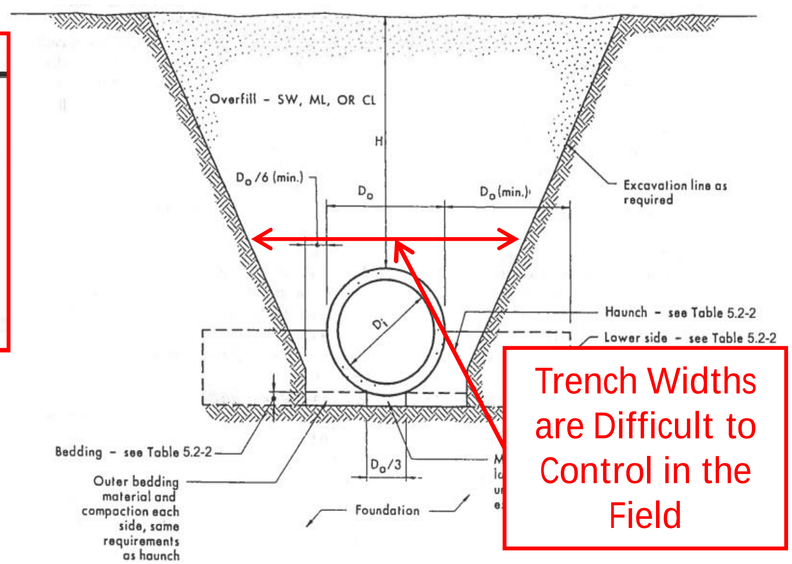
Heger Positive Projection Load

- Heger and Selig developed a simplified load calculation method based on the new SIDD installation types
- Only positive projection conditions considered
- Load coefficients developed with SPIDA
- Applied load = Prism load x Vertical Arching Factor (VAF)



Installation Type	VAF	HAF	A1	A2	A3	A4	A5	A6	a	b	c	e	f	u	v
1	1.35	0.45	0.62	0.73	1.35	0.19	0.08	0.18	1.40	0.40	0.18	0.08	0.05	0.80	0.80
2	1.40	0.40	0.85	0.55	1.40	0.15	0.08	0.17	1.45	0.40	0.19	0.10	0.05	0.82	0.70
3	1.40	0.37	1.05	0.35	1.40	0.10	0.10	0.17	1.45	0.36	0.20	0.12	0.05	0.85	0.60
4	1.45	0.30	1.45	0.00	1.45	0.00	0.11	0.19	1.45	0.30	0.25	0.00	-	0.90	-

Installation Type	VAF	HAF
1	1.35	0.45
2	1.40	0.40
3	1.40	0.37
4	1.45	0.30



Estimating Wall Forces

- Heger and Selig utilized SPIDA to assess and develop load coefficients for the new SIDD installations types

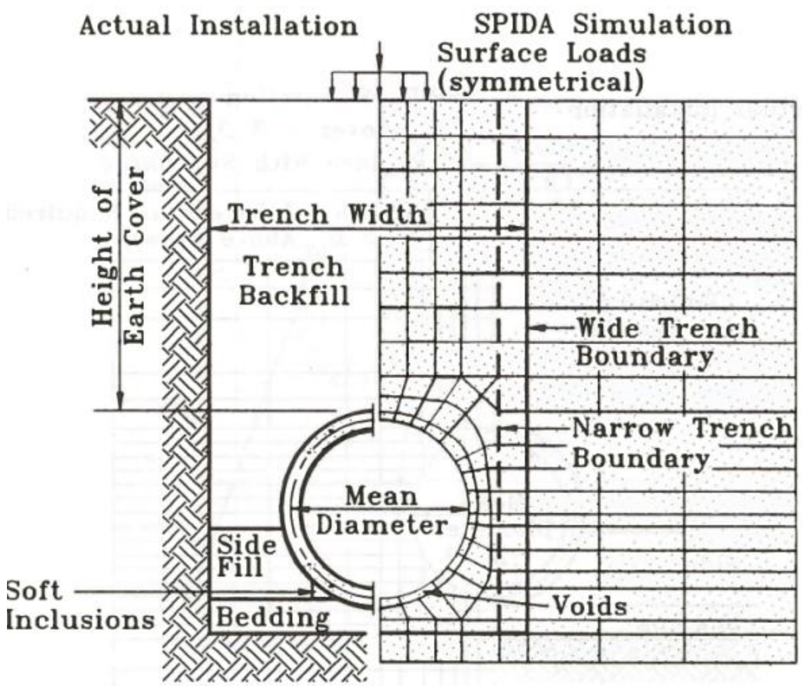


TABLE C-3.1. Installation Type 1 Coefficients

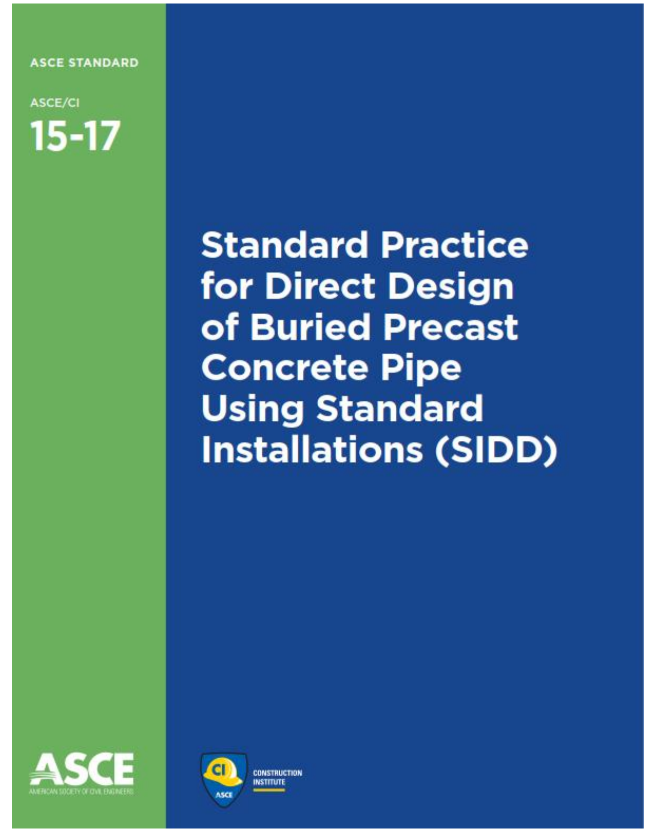
Location	Load Type	Coefficients Cm_i	Cn_i	Cv_i
Invert	W_p	.225	.077	
	W_e	.091	.188	
	W_f	.088	−.445	
	W_{L1}	.075	.250	
	W_{L2}	.165	−.046	
Crown	W_p	.079	−.077	
	W_e	.083	.157	
	W_f	.057	−.187	
	W_{L1}	.068	.200	
	W_{L2}	.236	.046	
Springline 90°	W_p	−.091	.249	
	W_e	−.077	.500	
	W_f	−.064	−.068	
	W_{L1}	−.065	.500	
	W_{L2}	−.154	.500	
Critical Shear Invert $\theta_v = 12°$	W_p		.174	.437
	W_e		.219	.143
	W_f		−.408	.141
	W_{L1}		.270	.150
Critical Shear Crown $\theta_v = 159°$	W_p		−.055	.083
	W_e		.205	.117
	W_f		−.176	.062
	W_{L1}		.250	.100

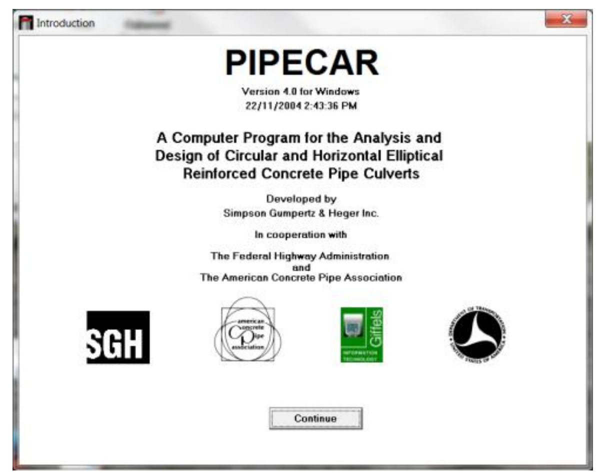
Direct Design

- Proposed in Heger's 1988 paper "New Installation Designs for Buried Concrete Pipe"
- Incorporates SIDD Installations and SPIDA developed load coefficients
- Incorporates limit states design methodology
- Proposed steel reinforcement design methods to counteract the following applied wall forces:
  - Bending moments
  - Wall thrust
  - Diagonal tension (shear)
  - Radial tension

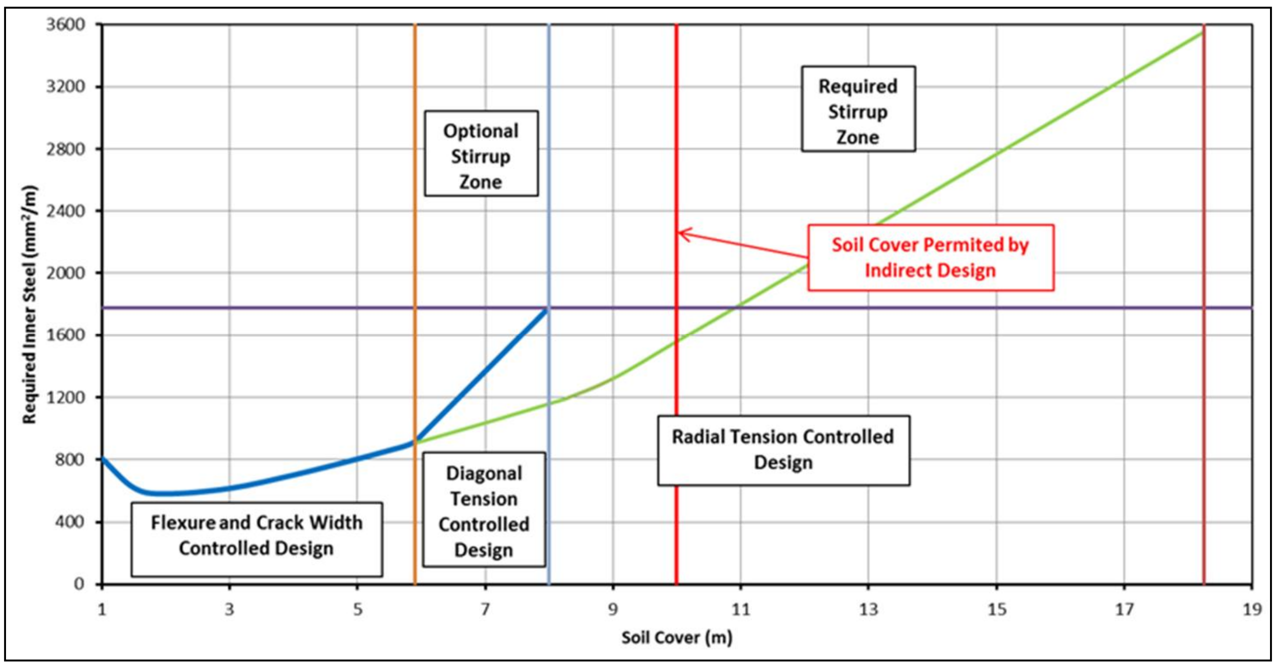
ASCE 15 and PIPECAR

- ASCE 15 – Standard Practice for Direct Design of Buried Precast Concrete Pipe Using Standard Installations (SIDD)
  - Originally published in 1993 subsequently updated in 1998 and 2017
  - Outlines SIDD installation requirements and direct design methodology
- Computerized design program PIPECAR™
  - Developed by Frank Heger for the ACPA
  - Direct design of RCP for a myriad of design and installation conditions
- Direct design and SIDD installations have now been adopted by both AASTHO and CSA





Transition from Indirect to Direct Design

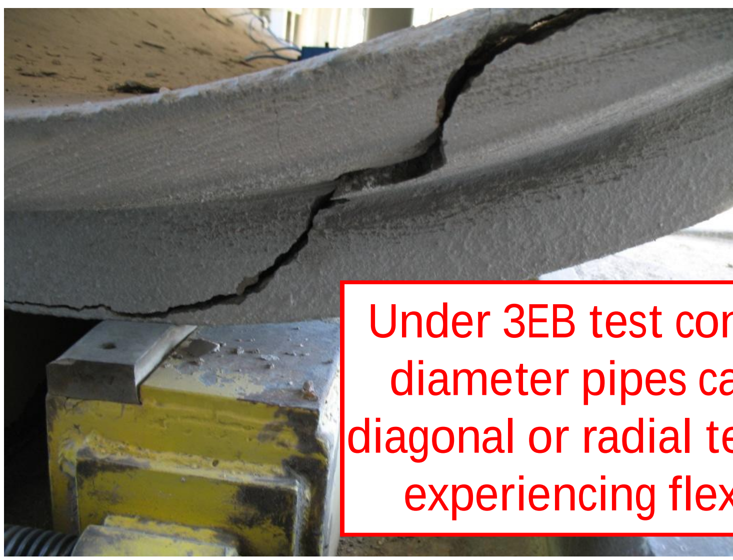


Limits of Indirect Design

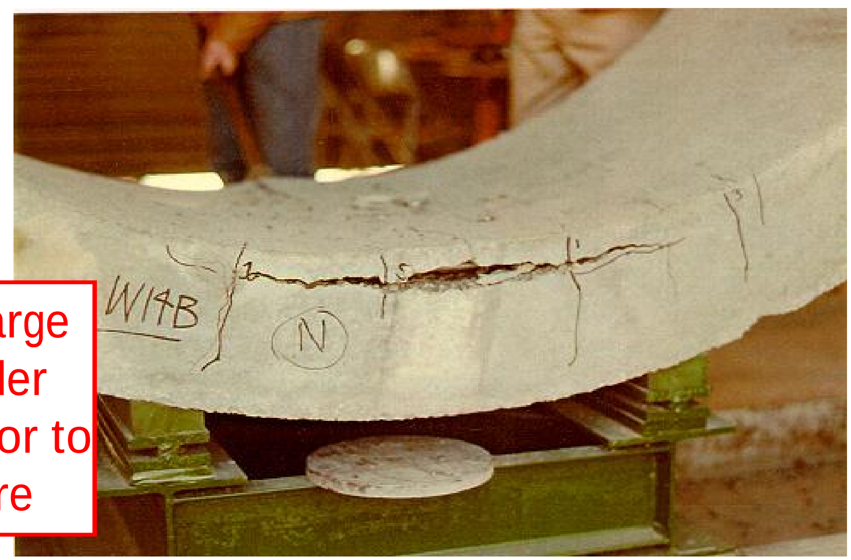
- Indirect design was developed based on empirical testing on small to intermediate diameter pipe (<36") under loading conditions typical of the time (<15')
- Failure modes recognized at the time were limited to flexural failure
    - Testing of unreinforced clay tile and concrete pipe
- 3EB tests do not directly assess diagonal or radial tension failure modes which govern under large external loading conditions

Diagonal and Radial Tension

- Pipes designed to withstand applied flexural stresses may not contain sufficient reinforcing to withstand imparted diagonal tension forces
- If not confirmed, mobilization of tensile steel under high loads may result in radial tension failure

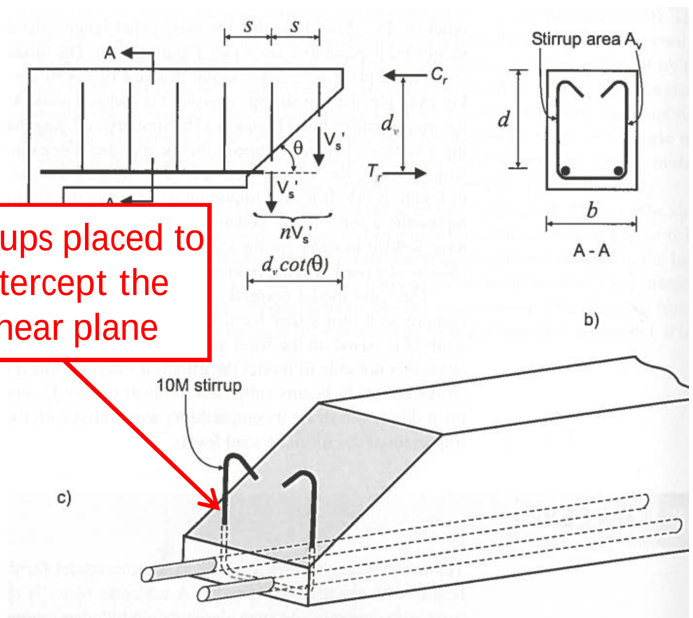


Under 3EB test conditions large diameter pipes can fail under diagonal or radial tension prior to experiencing flexural failure



Reinforcing for Diagonal Tension

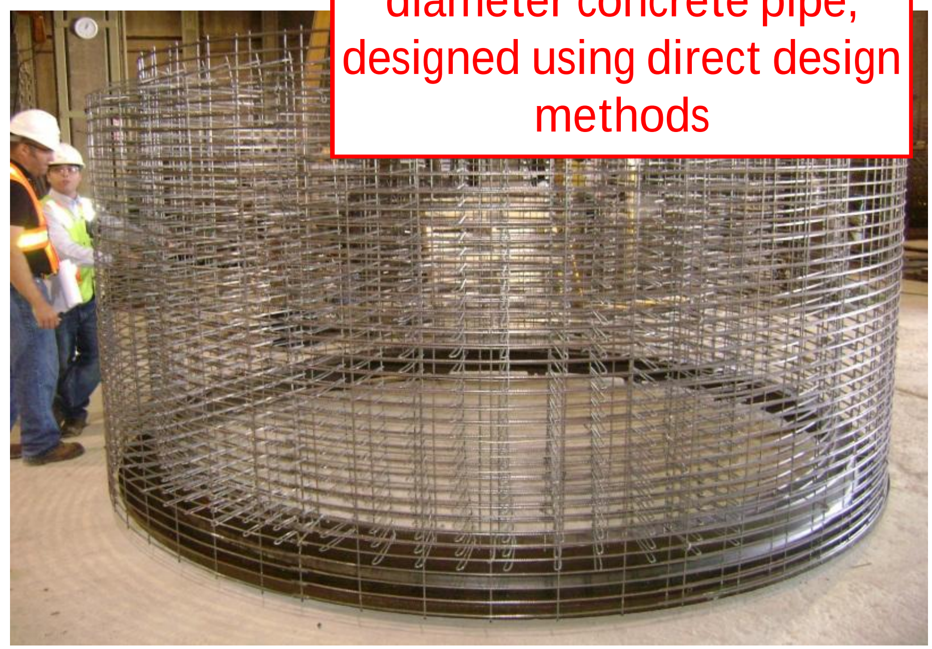
- Diagonal tension is resisted by:
  - Placement of additional radial reinforcing steel (to a point)
  - Placement of stirrups



Stirrups placed to intercept the shear plane

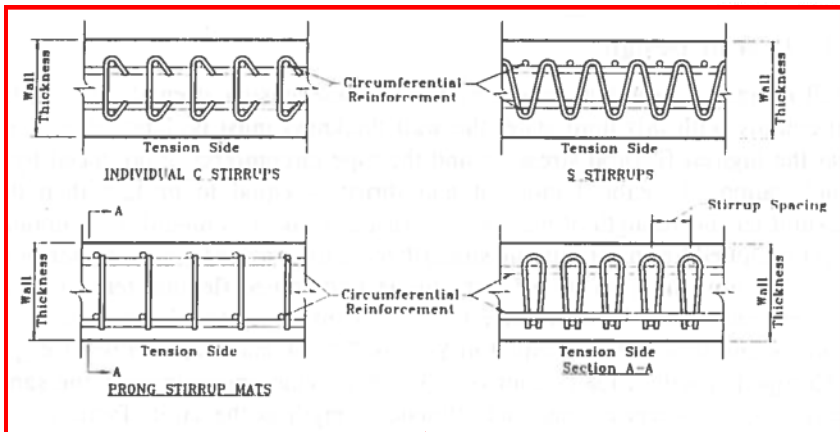
(Brzev et al 2006)

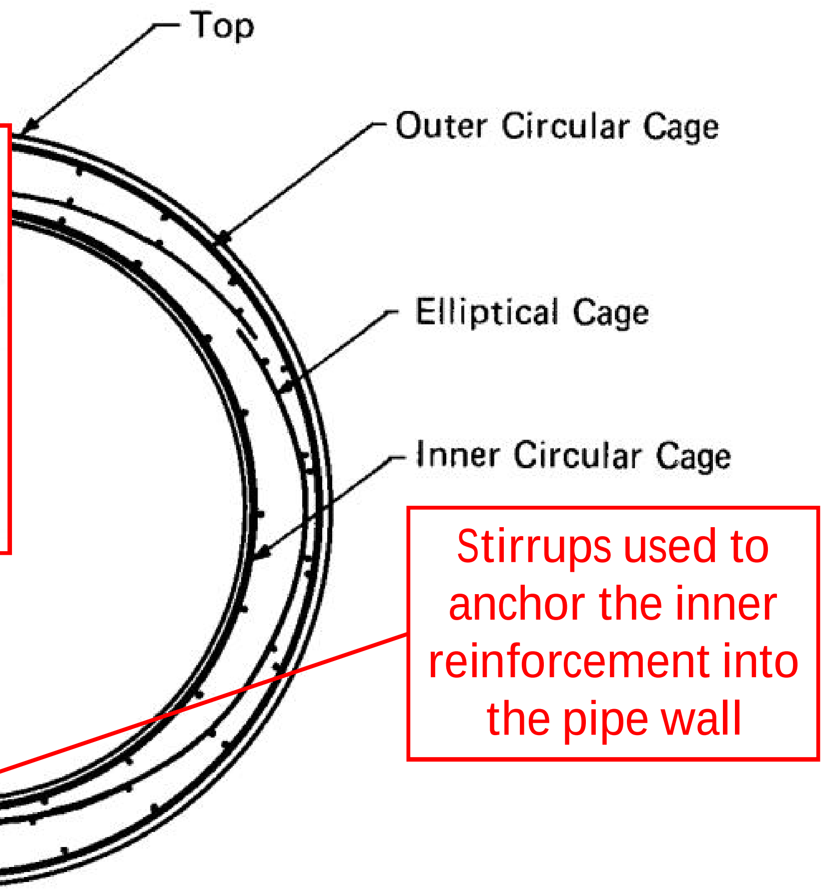
Heavily reinforced 10' diameter concrete pipe, designed using direct design methods



Reinforcing for Radial Tension

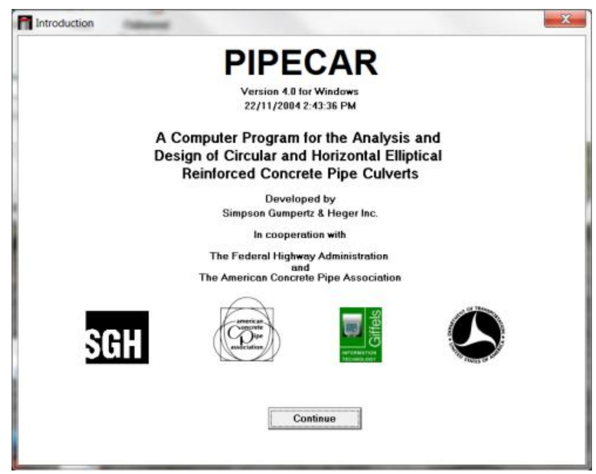
- Stirrups must be employed to overcome radial tension forces

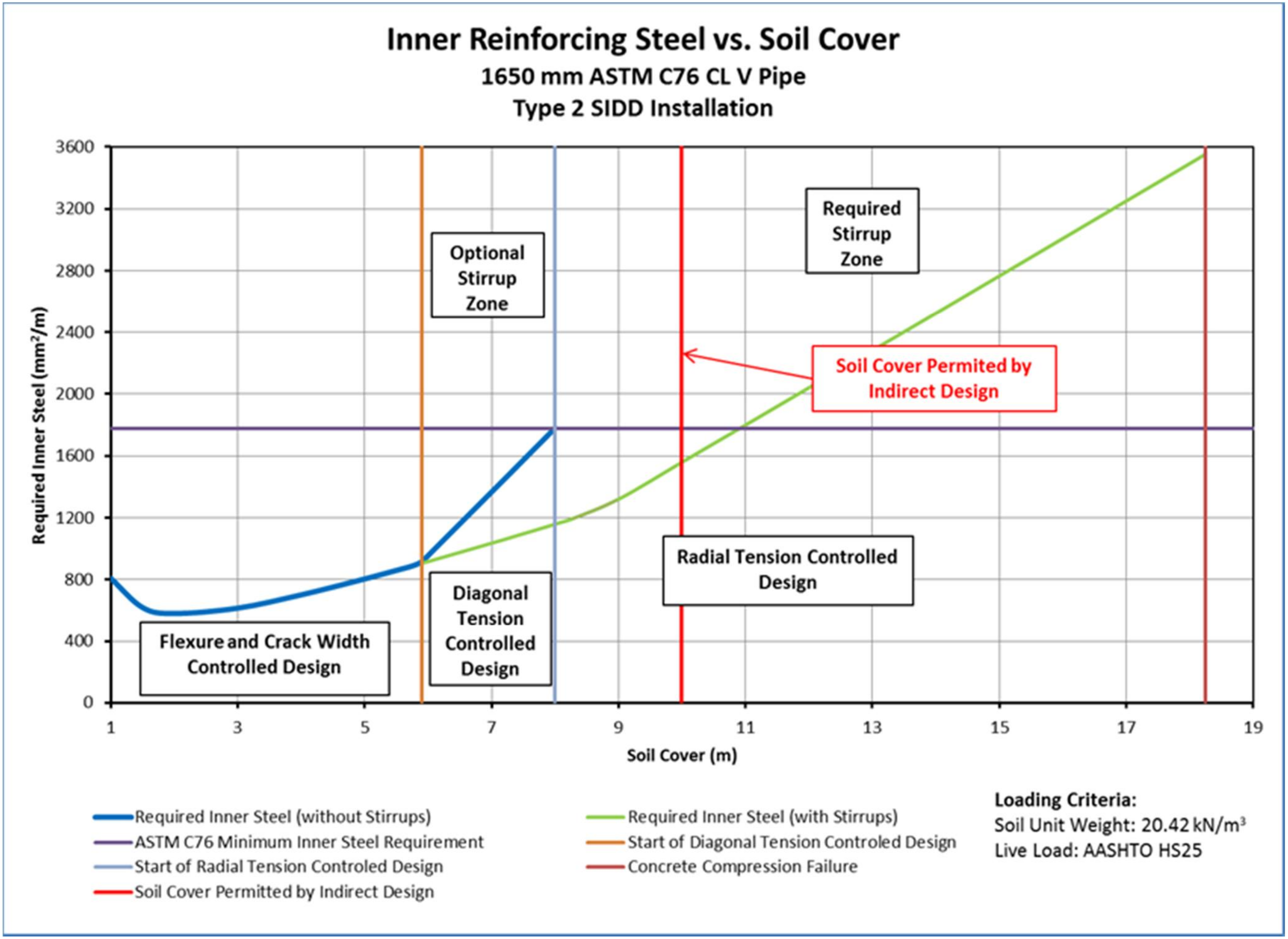




Transitioning from Indirect to Direct Design

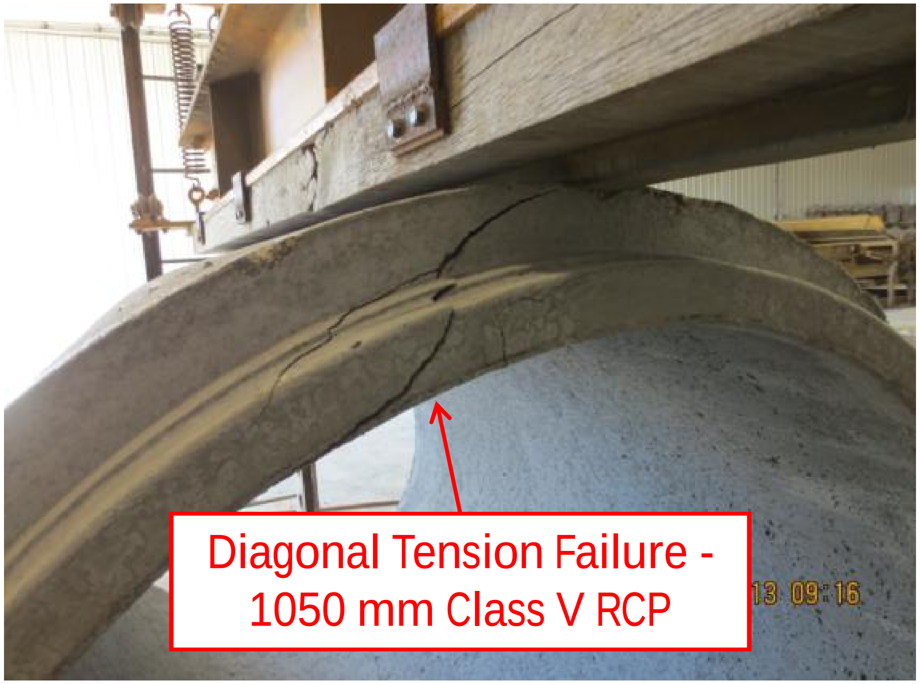
- Determine the transition from a flexural controlled failure to diagonal and/or radial tension controlled failure
- Requires the direct design methodologies (i.e. hand calcs or PIPECAR^{TM}




Inner Reinforcing Steel vs. Soil Cover
1650 mm ASTM C76 CL V Pipe
Type 2 SIDD Installation
Required Inner Steel (mm²/m)
3600
3200
2800
2400
2000
1600
1200
800
400
0
1
3
5
7
9
11
13
15
17
19
Soil Cover (m)
Optional Stirrup Zone
Required Stirrup Zone
Soil Cover Permited by Indirect Design
Diagonal Tension Controlled Design
Radial Tension Controlled Design
Flexure and Crack Width Controlled Design
Required Inner Steel (without Stirrups)
ASTM C76 Minimum Inner Steel Requirement
Start of Radial Tension Controled Design
Soil Cover Permitted by Indirect Design
Required Inner Steel (with Stirrups)
Start of Diagonal Tension Controled Design
Concrete Compression Failure
Loading Criteria:
Soil Unit Weight: 20.42 kN/m³
Live Load: AASHTO HS25

Verification

- Governing failure modes
- Bending moment capacity
- Diagonal tension capacity



Pipe Diameter (mm)	3_{EB} Testing		Pipecar Analysis @ at Soil Cover Limit (Type 2)		Pipecar Analysis @ at Soil Cover Limit (Type 3)	
	Bending Moment (kN*m/m)	Shear (kN/m)	Bending Moment (kN*m/m)	Shear (kN/m)	Bending Moment (kN*m/m)	Shear (kN/m)
1050	42.79	112.63	36.23	99.36	35.32	98.15
1650	101.10	167.72	82.23	136.67	81.29	136.87

Verification

- Governing failure modes
- Bending moment capacity
- Diagonal tension capacity

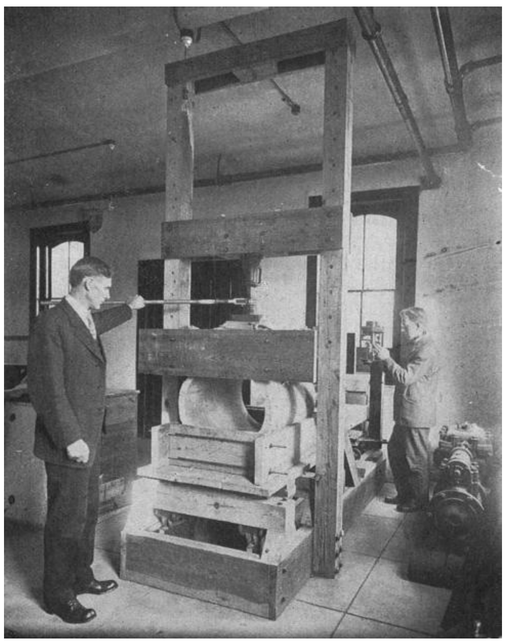
Pipe Diameter (mm)	3_{EB} Testing		Pipecar Analysis @ at Soil Cover Limit (Type 2)		Pipecar Analysis @ at Soil Cover Limit (Type 3)	
	Bending Moment (kN*m/m)	Shear (kN/m)	Bending Moment (kN*m/m)	Shear (kN/m)	Bending Moment (kN*m/m)	Shear (kN/m)
1050	42.79	112.63	36.23	99.36	35.32	98.15
1650	101.10	167.72	82.23	136.67	81.29	136.87

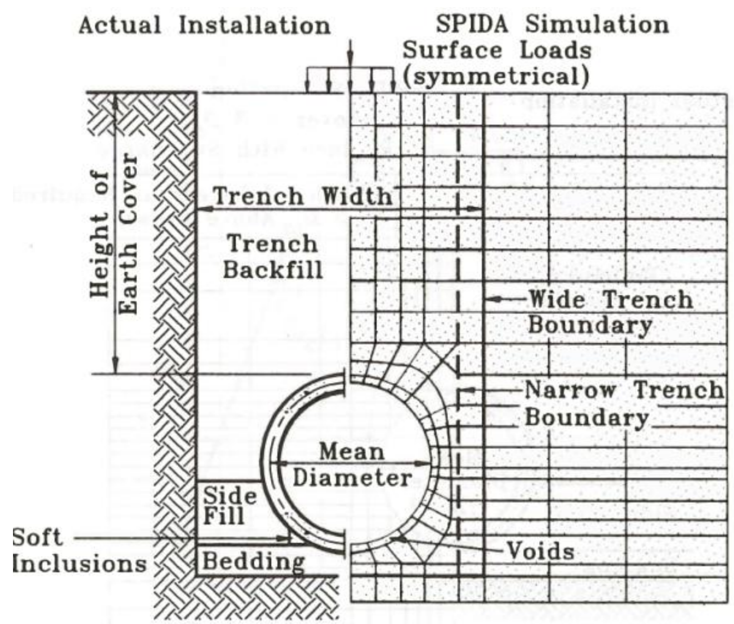
Verification

- Bending moment and shear capacity estimated using Heger's 3EB wall force coefficients
- Actual bending moment and diagonal tension capacity in excess of predicted capacities
- Result of:
  - Increased material strengths
  - Limit state design factors

Pipe Diameter (mm)	3_{EB} Testing		Pipecar Analysis @ at Soil Cover Limit (Type 2)		Pipecar Analysis @ at Soil Cover Limit (Type 3)	
	Bending Moment (kN*m/m)	Shear (kN/m)	Bending Moment (kN*m/m)	Shear (kN/m)	Bending Moment (kN*m/m)	Shear (kN/m)
1050	42.79	112.63	36.23	99.36	35.32	98.15
1650	101.10	167.72	82.23	136.67	81.29	136.87

Conclusion





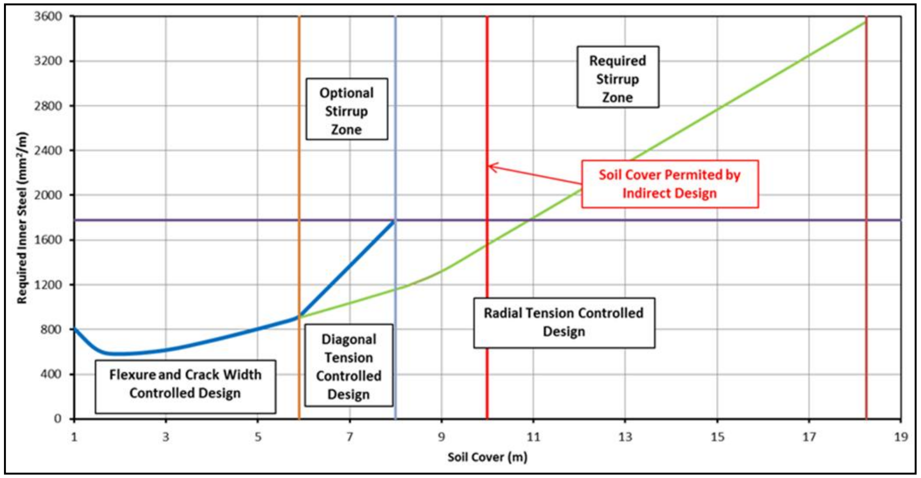
Actual Installation
SPIDA Simulation
Surface Loads
(symmetrical)
Height of Earth Cover
Trench Width
Trench Backfill
Wide Trench Boundary
Narrow Trench Boundary
Mean Diameter
Side Fill
Soft Inclusions
Bedding
Voids

Conclusion

- Indirect design has a long and successful service record for lower soil covers where diagonal and radial tension to not govern the design
- The use of indirect design for large diameter pipelines exposed to high external loads can ignore governing failure modes
- This exposes the Engineer, owner, and contractor to additional risk relating to failure and/or serviceability issues

Conclusion

- All large diameter pipes should be checked for governing failure modes regardless of pipe manufacturing methods (C76 or C1417)
- Available radial reinforcing should be confirmed whenever diagonal tension governs the design
- Direct design should be employed anytime stirrups are required



Conclusion

- Use in indirect design in deep cut applications will result in a pipe that's vulnerable to:
  - Excessive cracking, exceeding service cracking criteria
  - Premature degradation
  - Ultimate failure

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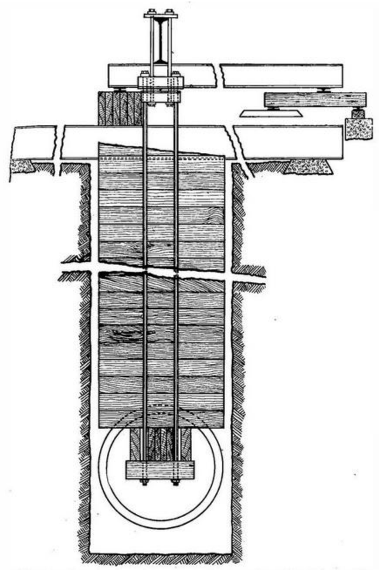
EVERY DAY MATTERS

American Concrete Pipe Association



Questions?

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