CAST-IN-PLACE EARTH REINFORCED CONCRETE PIPE ALTERNATIVE STORM DRAIN SYSTEM

City of Scottsdale Desert Greenbelt
PIMA ROAD THREE BASINS (PR3B) PROJECT
Hydraulic and Structural Analysis

FOR

STANTEC CONSULTING, INC.
7776 Pointe Parkway W. Suite 290
Phoenix AZ 85044

BY

TERRAIN ENGINEERING, INC.
25740 WASHINGTON AVENUE
MURRIETA, CA 92562
TELEPHONE: (909) 698-8471
FAX: (909 698-7898)

Registered Professional Engineer (Civil)
CERTIFICATE NO.
25868
CURTISS W
GILLEY
Date Signed 4/14/98
ARIZONA U.S.A.

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SITE EVALUATION

STRUCTURAL ANALYSIS
AND
CALCULATIONS

Site Evaluation, Structural Analysis and Calculations for use of Cast-In-Place Earth Reinforced Concrete Pipe

This firm has completed a site evaluation and structural analysis for the use of cast-in-place earth reinforced concrete pipe as an alternative to the conventional use of reinforced concrete pipe. This report presents the results of the site evaluation and structural analysis.

The soil conditions in the project area from construction experience in this area and from a comprehensive review of " Geotechnical Investigation Report, Desert Greenbelt Phase I Channels, Pima Road & Cap Canal, Scottsdale , Arizona prepared by Agra Earth & Environmental, Inc., August 25, 1995, are very suitable for the construction of cast-in-place concrete pipe. Specifically, within the pipe zone area thy are described as " very firm to hard interbedded layers of silty to clayey sands and silty sands with gravel". The soil test data indicate that the project area soils are capable of providing the lateral support required for the construction of cast-in-place earth reinforced concrete pipe. Should an area be encountered where there is a deficiency in the cementitious or cohesive properties of the soil where the trench walls in the pipe zone will not stand vertical, over excavation and recompaction to 90% maximum dry density will have to be accomplished.

A cast-in-place earth reinforced concrete pipe system is constructed as a continuous single-stage monolithic casting in a round bottom trench excavated to the design outer diameter of the pipe. The trench is actually a trench form for a self propelled casting machine to slip form the pipe directly in the trench "neat" to the excavated trench wall and invert. This is in contrast to a reinforced concrete pipe system which is constructed by placing factory manufactured pipe in an excavated trench with bedding and placement of compacted backfill material around and over the pipe.

Cast-in-Place Earth Reinforced Concrete Pipe is a soil structure interaction dependent product that relies upon competent soils for the development of the lateral force field needed to contain the maximum tensile stress in the pipe ring to that which is safely less than that of the rupture stress of the concrete. This is in contrast to steel reinforced concrete pipe where reinforcing steel in the pipe ring is utilized with compacted bedding to provide the force field necessary to keep the tensile stresses in the pipe ring from exceeding the allowable design stresses

The analysis of earth reinforced cast-in-place concrete pipe falls in the category of small deflection theory. The structural computational program employs classical principles of two dimensional plane strain utilizing Roark's Formulas for Stress and Strain (6th Edition by Warren C, Young, 1989, Circular rings and arches, Chapter8.) The structural analysis program used is CAPLCOP ST 1.04.

These calculations are prepared on the worst case situations where imposition of the most severe loadings are used to obtain the highest stresses within the pipe. A structural analysis supporting the use of Cast-In-Place Earth Reinforced Concrete Pipe (CIPCP) as an alternative to the reinforced concrete pipe (RCP) specified for the storm drain system for the subject project has been performed.

The vertical loading applied is a combination of Marston earth load with HS2O AASHTO live loading. AASHTO live load impact is included where the cover is 3' or less. Th actual live load applied is a 16,000 lb. wheel load taken as a point load (more conservative than the AASHTO footprint load) spread to the pipe at 7H:8V. The dead weight of the pipe is included. The stress calculations are made with the pipe empty and full of water. Hydrostatic loading is included where the hydraulic grade line is above the pipe soffit.

The lateral loading applied, which provides the counter moments to resist the moments resulting from the vertical load, relies upon the principles of soil structure interaction since the pipe is cast in a trench having vertical side walls and an invert area shaped to the pipe outside diameter (earth reinforcement). For CIPCP, the vertical loading pushing downward causes the pipe to deflect outward to the trench walls (structure pushes to soil, passive movement). This passive movement activates the passive pressure characteristic of the soil, Kp.

Rankine theory for the development of the lateral pressure coefficient depends on the soil angle of internal friction ϕ. This value for CIPCP varies from a lower limit, $Kp = 1 - \sin \phi$, "at rest", to an upper limit of $Kp = 1 + \sin \phi / 1 - \sin \phi$. The amount of the available lateral force activated depends on the ratio of anticipated wall movement to wall height and the internal angle of friction of the soil. The better the soil the less movement required to activate higher lateral resisting forces (reference the enclosed figure, Relationship between wall movement and earth pressure, Clough, G.W., and Ducan, J.M.1991. Earth Pressures. Foundation Engineering Handbook, ed. H-Y Fang, pp 224-235). The referenced Geotechnical report indicates angles of internal friction of up to 56 degrees. For conservatism, the angle of internal friction used to determine the passive pressure coefficients utilized in the stress calculations in this report is 30 degrees. For this CIPCP design, a

pressure coefficient Kp of 0.5 to 2.2 is used. This upper value is based on amount of lateral pressure needed to keep the stresses in the pipe ring to those which the concrete can sustain. The maximum upper limit is the full passive pressure Kp = 3.0. These conservative Kp for lateral pressure combined with the selection of an appropriate concrete strength provide the criteria used to calculate design stresses in the pipe ring.

The program at user selected points pf the pipe's cross-section, determines moments, thrust (ring, compression), and shears. The program queries the user for the following information: nominal diameter, distance from top of crown to top of trench, total fill height, unit weight of the soil, Rankine coefficient of lateral pressure, ultimate strength and modulus of rupture of the concrete, live load, hydrostatic head above crown (if full), and the number of points of the cross-section, between crown and invert, the user wishes to have analyzed. Usually 5 points (45 degrees) is used, but each 5 degrees can be selected which provide 37 points from crown to invert.

The program analyzes the cross-section for linear (Rankine) lateral loads from outer invert to top of haunch, (a more conservative loading than from top of pipe) and for horizontal distribution of vertical loads at crown and invert. The output are the stresses, and the associated factors of safety at the inner and outer pipe surface at the user selected points. For this analysis, the stresses and associated factors of safety are computed at 5 points from crown (0 degrees) to invert (180 degrees.)

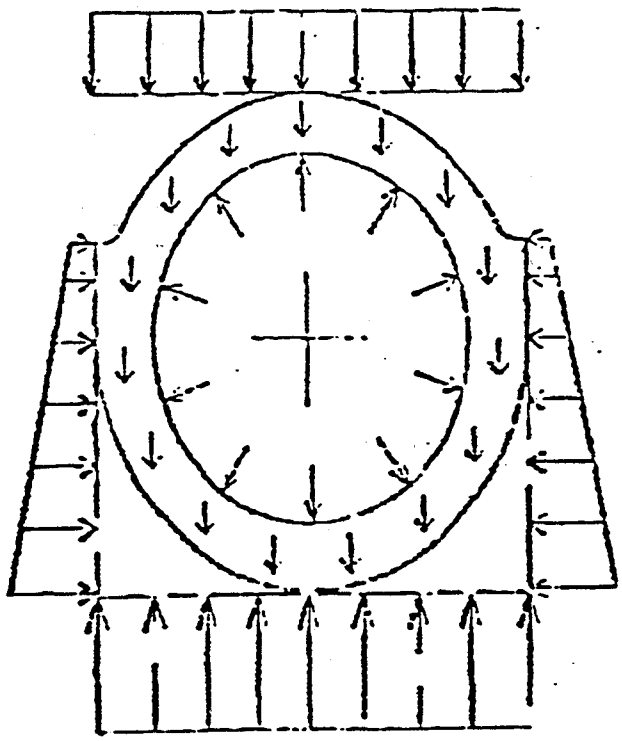
For these design situations, the stresses are measured against the modulus of rupture of 3000 psi compressive strength concrete to obtain a safety factor. The minimum recommended safety factor is 1.5. The analysis show minimum safety factors that exceed 1.5.As an additional safety factor, the soil is capable of providing for more support than that used in these calculations, i.e., Rankine of 0.5 to 1.2 with a maximum of 3.0. The following table summarizes the design situations and stresses. When reviewing these design situations, note that the 108"dia. pipe requires 3 ft.of cover to carry a full 16000 lb. AASHTO live load. The design minimum cover of 1 ft.+/- will only handle live loads including impact of 5000 lb. +/-. In actuality, the pipe will carry the load, but the calculations will not support it.

PIPE DIA.(IN.)	COVER (FT.)	HEAD (FT.)	RANKINE	SAFETY FAC.
120 (A)	4.0	4.0	0.5	1.79
120 (B)	19.0	15.0	0.6	1.62
108 (A)	1.0	0.0	2.2	1.68
108 (B)	10.0	7.5	0.5	1.66
108 (C)	3.0	0.0	0.5	1.54
96	5.0	0.0	0.5	2.07

Construction specifications for Cast-in-Place Concrete Pipe are contained in Arizona Department of Transportation, Standard Specifications. The most recent version in use is a "stored" specification. This is a complete rewrite of the specification contained in the latest printed edition of the ADOT standards. This specification is the recommended specification for construction as it contains the most up to date standards and a defined Quality Assurance Program.

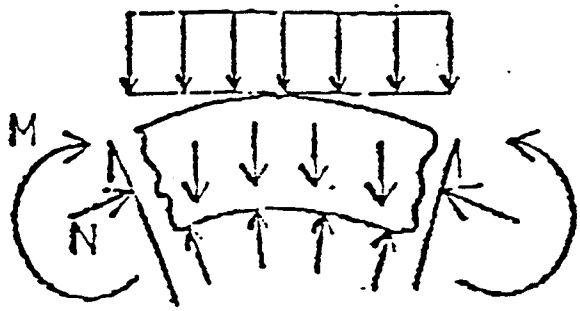
For additional information regarding structural capability of CIPCP, refer to enclosed copies of papers prepared by myself and Lester Gabriel, P.E., Ph.D. The paper entitled "Field Test of 72" Diameter Cast-in-Place Concrete Pipe" was published in the ASCE Journal of Transportation Engineering, January/February 1992. The paper entitled "Field Performance of Structures and Nondestructive Evaluation of Subsurface Infrastructure" was published in the Transportation Research Record, No. 1415, Soils, Geology, and Foundations, Washington, D.C., in 1993.

LOADING DIAGRAM



Not to Scale

Pipe section showing loading and resulting moment, thrust and shear stresses.



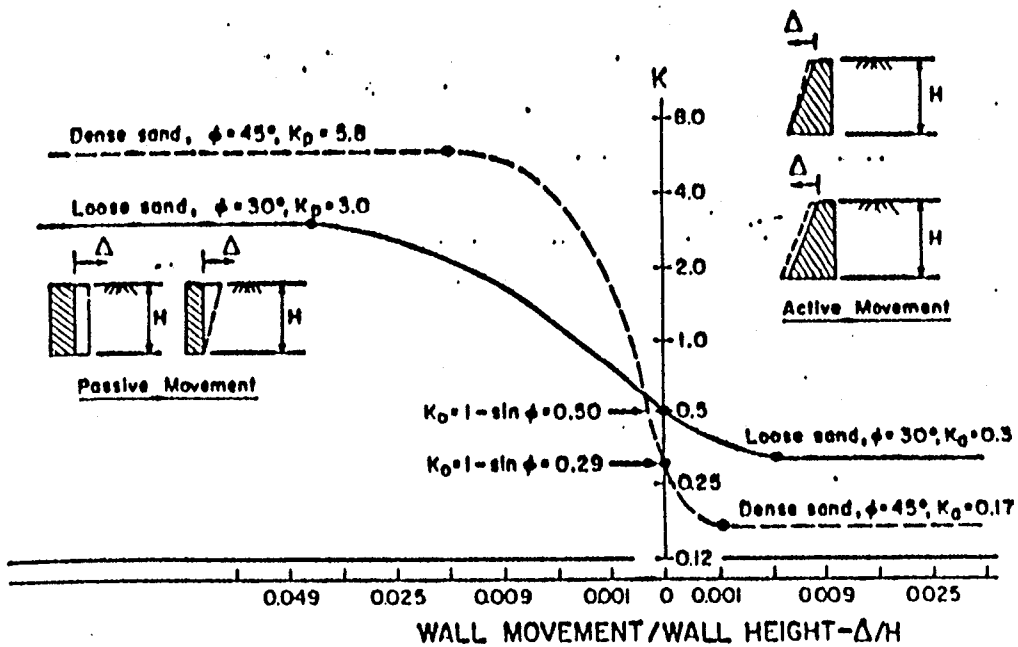


FIGURE 21.2 Relationship between wall movement and earth pressure. (After Clough, G. W. and Duncan, J. M. 1991. Earth Pressures. In *Foundation Engineering Handbook*, ed. H-Y. Fang, pp. 224–235. Van Nostrand Reinhold, New York.)

TERRAIN ENGINEERING INC.

6940 Tremont Rd

Dixon, CA 95620

CAST-IN-PLACE EARTH REINFORCED CONCRETE PIPE

STRUCTURAL ANALYSIS

CAPLCOP v. 1.04

TITLE: PIMA ROAD THREE BASINS (PIMA2REV.120A)
LOCATION: SCOTTSDALE, AZ
DATE: 4- 5-1998
TIME: 12:35

PIPE DATA	
NOMINAL DIAMETER (in)=	120
MIN. WALL THICKNESS (in)=	12.0
X-SECT. MIN AREA (in**2)=	4976
MOMENT OF INTERIA (in**4)=	144.0
AREA FOR STRESS CALC (in**2)=	12.0
DISTANCE FROM MID-SEC TO NA (in)=	.2

LIVE LOAD DATA	
DESCRIPTION=	HS20 W/IMPACT
POINT LOAD (LBS)=	16000.0
SOIL DISTRIBUTION=	7.00 ACROSS
=	8.00 DOWN
UNIFORM LOAD ON THE PIPE (psi)=	2.3
WIDTH OF UNIFORM LOAD (in)=	84.0

SOIL DATA	
TRENCH HEIGHT (ft)=	3.0
TOTAL COVER HEIGHT (ft)=	4.0
UNIT WEIGHT OF FILL SOIL (pcf)=	120
UNIT WEIGHT OF IN-SITU SOIL (pcf)=	115
RANKINE COEFFICIENT OF IN-SITU SOIL=	.5
MARSTON LOAD (psi)=	3.5

MISC DATA	
CONCRETE STRENGTH (psi)=	3000
MODULUS RUPTURE (psi)=	493
WATER HEIGHT OVER PIPE CROWN (ft)=	4.0
UNIT WEIGHT OF CONCRETE (pcf)=	150
UNIT WEIGHT OF WATER (pcf)=	62.4

PIMA ROAD THREE BASINS (PIMA2REV.120A)

RESULTS OF ANALYSIS

MOMENTS AT LOCATIONS IN PIPE CROSS SECTION

LOCATION (deg from crown)	MOMENT MARSTON (in-lbs/in)	MOMENT LATERAL (in-lbs/in)	MOMENT DEAD (in-lbs/in)	MOMENT LIVE (in-lbs/in)	MOMENT WATER (in-lbs/in)
.0	3760	-4064	1555	2456	1946
45.0	-20	-318	142	-13	243
90.0	-3801	4433	-1791	-2482	-2181
135.0	-20	270	-161	-13	-407
180.0	3760	-4897	1990	2456	3259

RING THRUSTS AT LOCATIONS IN PIPE CROSS SECTION

LOCATION (deg from crown)	THRUST MARSTON (lbs/in)	THRUST LATERAL (lbs/in)	THRUST DEAD (lbs/in)	THRUST LIVE (lbs/in)	THRUST WATER (lbs/in)
.0	0	-212	11	0	96
45.0	-114	-121	-29	-74	70
90.0	-228	0	-107	-149	34
135.0	-114	-147	-77	-74	112
180.0	0	-326	-10	0	218

SHEARS AT LOCATIONS IN PIPE CROSS SECTION

LOCATION (deg from crown)	SHEAR MARSTON (lbs/in)	SHEAR LATERAL (lbs/in)	SHEAR DEAD (lbs/in)	SHEAR LIVE (lbs/in)	SHEAR WATER (lbs/in)
.0	0	0	0	0	0
45.0	-114	180	-45	97	-55
90.0	0	408	-10	32	-17
135.0	115	450	62	-113	76
180.0	0	0	0	-298	43

PIMA ROAD THREE BASINS (PIMA2REV.120A)

TOTALS (without water loading)

LOCATION (deg)	MOMENT (in/lbs/in)	THRUST (lbs/in)	SHEAR (lbs/in)
.0	3705	-201	0
45.0	-211	-340	116
90.0	-3643	-486	428
135.0	74	-415	512
180.0	3307	-337	-298

STRESSES (p.s.i.) - without head & water Load
Tension (+); Compression (-)

LOCATION	OD FIBER	SAFETY FACTOR	ID FIBER	SAFETY FACTOR
.0	-175	17.06	133	3.71
45.0	-18	155.12	-36	81.12
90.0	116	4.25	-187	15.98
135.0	-37	79.33	-31	94.74
180.0	-169	17.63	105	4.68

MINIMUM FACTOR OF SAFETY= 3.71

STRESSES (p.s.i.) - with head & water load
Tension (+); Compression (-)

LOCATION	OD FIBER	SAFETY FACTOR	ID FIBER	SAFETY FACTOR
.0	-230	13.01	240	2.05
45.0	-2	974.29	0	5910.82
90.0	233	2.11	-251	11.89
135.0	10	50.19	-17	166.15
180.0	-270	11.07	276	1.79

MINIMUM FACTOR OF SAFETY= 1.79

TERRAIN ENGINEERING INC.

6940 Tremont Rd

Dixon, CA 95620

CAST-IN-PLACE EARTH REINFORCED CONCRETE PIPE

STRUCTURAL ANALYSIS

CAPLCOP v. 1.04

TITLE: PIMA ROAD THREE BASINS (PIMA2REV.120B)
LOCATION: SCOTTSDALE, AZ
DATE: 4- 5-1998
TIME: 12:50

PIPE DATA

NOMINAL DIAMETER (in)=	120
MIN. WALL THICKNESS (in)=	12.0
X-SECT. MIN AREA (in**2)=	4976
MOMENT OF INTERIA (in**4)=	144.0
AREA FOR STRESS CALC (in**2)=	12.0
DISTANCE FROM MID-SEC TO NA (in)=	.2

LIVE LOAD DATA

DESCRIPTION=	HS20
POINT LOAD (LBS)=	16000.0
SOIL DISTRIBUTION=	7.00 ACROSS
=	8.00 DOWN
UNIFORM LOAD ON THE PIPE (psi)=	.1
WIDTH OF UNIFORM LOAD (in)=	144.0

SOIL DATA

TRENCH HEIGHT (ft)=	3.0
TOTAL COVER HEIGHT (ft)=	19.0
UNIT WEIGHT OF FILL SOIL (pcf)=	120
UNIT WEIGHT OF IN-SITU SOIL (pcf)=	115
RANKINE COEFFICIENT OF IN-SITU SOIL=	.6
MARSTON LOAD (psi)=	14.2

MISC DATA

CONCRETE STRENGTH (psi)=	3000
MODULUS RUPTURE (psi)=	493
WATER HEIGHT OVER PIPE CROWN (ft)=	15.0
UNIT WEIGHT OF CONCRETE (pcf)=	150
UNIT WEIGHT OF WATER (pcf)=	62.4

PIMA ROAD THREE BASINS (PIMA2REV.120B)

RESULTS OF ANALYSIS

MOMENTS AT LOCATIONS IN PIPE CROSS SECTION

LOCATION (deg from crown)	MOMENT MARSTON (in-lbs/in)	MOMENT LATERAL (in-lbs/in)	MOMENT DEAD (in-lbs/in)	MOMENT LIVE (in-lbs/in)	MOMENT WATER (in-lbs/in)
.0	15351	-12747	1555	109	1946
45.0	-84	-425	142	0	243
90.0	-15520	13103	-1791	-109	-2181
135.0	-84	281	-161	0	-407
180.0	15351	-13748	1990	109	3259

RING THRUSTS AT LOCATIONS IN PIPE CROSS SECTION

LOCATION (deg from crown)	THRUST MARSTON (lbs/in)	THRUST LATERAL (lbs/in)	THRUST DEAD (lbs/in)	THRUST LIVE (lbs/in)	THRUST WATER (lbs/in)
.0	0	-729	11	0	96
45.0	-467	-382	-29	-2	70
90.0	-935	0	-107	-6	34
135.0	-467	-414	-77	-2	112
180.0	0	-866	-10	0	218

SHEARS AT LOCATIONS IN PIPE CROSS SECTION

LOCATION (deg from crown)	SHEAR MARSTON (lbs/in)	SHEAR LATERAL (lbs/in)	SHEAR DEAD (lbs/in)	SHEAR LIVE (lbs/in)	SHEAR WATER (lbs/in)
.0	0	0	0	0	0
45.0	-467	650	-45	4	-55
90.0	0	1438	-10	1	-17
135.0	468	1448	62	-4	76
180.0	0	0	0	-12	43

PIMA ROAD THREE BASINS (PIMA2REV.120B)

TOTALS (without water loading)

LOCATION (deg)	MOMENT (in/lbs/in)	THRUST (lbs/in)	SHEAR (lbs/in)
.0	4266	-718	0
45.0	-369	-883	140
90.0	-4319	-1049	1428
135.0	33	-963	1973
180.0	3701	-877	-12

STRESSES (p.s.i.) - without head & water Load
Tension (+); Compression (-)

LOCATION	OD FIBER	SAFETY FACTOR	ID FIBER	SAFETY FACTOR
.0	-242	12.34	112	4.38
45.0	-57	51.90	-88	33.84
90.0	98	5.03	-261	11.45
135.0	-81	36.68	-78	37.97
180.0	-231	12.93	76	6.46

MINIMUM FACTOR OF SAFETY= 4.38

STRESSES (p.s.i.) - with head & water load
Tension (+); Compression (-)

LOCATION	OD FIBER	SAFETY FACTOR	ID FIBER	SAFETY FACTOR
.0	-240	12.47	277	1.78
45.0	16	31.49	5	98.08
90.0	272	1.81	-268	11.14
135.0	23	21.39	-7	365.56
180.0	-275	10.88	304	1.62

MINIMUM FACTOR OF SAFETY= 1.62

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Dixon, CA 95620

CAST-IN-PLACE EARTH REINFORCED CONCRETE PIPE

STRUCTURAL ANALYSIS

CAPLCOP v. 1.04

TITLE: PIMA ROAD THREE BASINS (PIMA2REV.108A)
LOCATION: SCOOTSDALE, AZ
DATE: 4- 5-1998
TIME: 13: 3

PIPE DATA	
NOMINAL DIAMETER (in)=	108
MIN. WALL THICKNESS (in)=	10.5
X-SECT. MIN AREA (in**2)=	3909
MOMENT OF INTERIA (in**4)=	96.5
AREA FOR STRESS CALC (in**2)=	10.5
DISTANCE FROM MID-SEC TO NA (in)=	.2

LIVE LOAD DATA	
DESCRIPTION=	HS20
POINT LOAD (LBS)=	16000.0
SOIL DISTRIBUTION=	7.00 ACROSS
=	8.00 DOWN
UNIFORM LOAD ON THE PIPE (psi)=	.4
WIDTH OF UNIFORM LOAD (in)=	129.0

SOIL DATA	
TRENCH HEIGHT (ft)=	3.0
TOTAL COVER HEIGHT (ft)=	10.0
UNIT WEIGHT OF FILL SOIL (pcf)=	120
UNIT WEIGHT OF IN-SITU SOIL (pcf)=	115
RANKINE COEFFICIENT OF IN-SITU SOIL=	.5
MARSTON LOAD (psi)=	8.1

MISC DATA	
CONCRETE STRENGTH (psi)=	3000
MODULUS RUPTURE (psi)=	493
WATER HEIGHT OVER PIPE CROWN (ft)=	7.5
UNIT WEIGHT OF CONCRETE (pcf)=	150
UNIT WEIGHT OF WATER (pcf)=	62.4

PIMA ROAD THREE BASINS (PIMA2REV.108A)

RESULTS OF ANALYSIS

MOMENTS AT LOCATIONS IN PIPE CROSS SECTION

LOCATION (deg from crown)	MOMENT MARSTON (in-lbs/in)	MOMENT LATERAL (in-lbs/in)	MOMENT DEAD (in-lbs/in)	MOMENT LIVE (in-lbs/in)	MOMENT WATER (in-lbs/in)
.0	7039	-5191	1097	317	1405
45.0	-36	-241	101	-1	174
90.0	-7112	5436	-1262	-319	-1575
135.0	-36	184	-113	-1	-291
180.0	7039	-5794	1403	317	2340

RING THRUSTS AT LOCATIONS IN PIPE CROSS SECTION

LOCATION (deg from crown)	THRUST MARSTON (lbs/in)	THRUST LATERAL (lbs/in)	THRUST DEAD (lbs/in)	THRUST LIVE (lbs/in)	THRUST WATER (lbs/in)
.0	0	-322	9	0	78
45.0	-238	-173	-23	-10	57
90.0	-477	0	-84	-20	27
135.0	-238	-194	-60	-10	90
180.0	0	-414	-8	0	176

SHEARS AT LOCATIONS IN PIPE CROSS SECTION

LOCATION (deg from crown)	SHEAR MARSTON (lbs/in)	SHEAR LATERAL (lbs/in)	SHEAR DEAD (lbs/in)	SHEAR LIVE (lbs/in)	SHEAR WATER (lbs/in)
.0	0	0	0	0	0
45.0	-238	283	-35	14	-44
90.0	0	631	-8	5	-13
135.0	239	652	48	-15	61
180.0	0	0	0	-42	34

PIMA ROAD THREE BASINS (PIMA2REV.108A)

TOTALS (without water loading)

LOCATION (deg)	MOMENT (in/lbs/in)	THRUST (lbs/in)	SHEAR (lbs/in)
.0	3260	-313	0
45.0	-179	-446	22
90.0	-3259	-583	627
135.0	32	-505	923
180.0	2964	-423	-42

STRESSES (p.s.i.) - without head & water Load
Tension (+); Compression (-)

LOCATION	OD FIBER	SAFETY FACTOR	ID FIBER	SAFETY FACTOR
.0	-212	14.11	142	3.47
45.0	-31	92.35	-51	57.62
90.0	127	3.88	-227	13.17
135.0	-49	60.03	-46	64.49
180.0	-205	14.53	116	4.24

MINIMUM FACTOR OF SAFETY= 3.47

STRESSES (p.s.i.) - with head & water load
Tension (+); Compression (-)

LOCATION	OD FIBER	SAFETY FACTOR	ID FIBER	SAFETY FACTOR
.0	-243	12.29	264	1.87
45.0	3	159.05	2	200.42
90.0	258	1.91	-268	11.17
135.0	15	33.11	-12	223.97
180.0	-280	10.68	296	1.66

MINIMUM FACTOR OF SAFETY= 1.66

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Dixon, CA 95620

CAST-IN-PLACE EARTH REINFORCED CONCRETE PIPE

STRUCTURAL ANALYSIS

CAPLCOP v. 1.04

TITLE: PIMA ROAD THREE BASINS (PIMA2REV.108B)
LOCATION: SCOTTSDALE, AZ
DATE: 4- 5-1998
TIME: 13:25

PIPE DATA	
NOMINAL DIAMETER (in)=	108
MIN. WALL THICKNESS (in)=	10.5
X-SECT. MIN AREA (in**2)=	3909
MOMENT OF INTERIA (in**4)=	96.5
AREA FOR STRESS CALC (in**2)=	10.5
DISTANCE FROM MID-SEC TO NA (in)=	.2

LIVE LOAD DATA	
DESCRIPTION=	MAINTENANCE
POINT LOAD (LBS)=	6000.0
SOIL DISTRIBUTION=	7.00 ACROSS
=	8.00 DOWN
UNIFORM LOAD ON THE PIPE (psi)=	13.6
WIDTH OF UNIFORM LOAD (in)=	21.0

SOIL DATA	
TRENCH HEIGHT (ft)=	1.0
TOTAL COVER HEIGHT (ft)=	1.0
UNIT WEIGHT OF FILL SOIL (pcf)=	120
UNIT WEIGHT OF IN-SITU SOIL (pcf)=	115
RANKINE COEFFICIENT OF IN-SITU SOIL=	2.2
MARSTON LOAD (psi)=	.9

MISC DATA	
CONCRETE STRENGTH (psi)=	3000
MODULUS RUPTURE (psi)=	493
WATER HEIGHT OVER PIPE CROWN (ft)=	.0
UNIT WEIGHT OF CONCRETE (pcf)=	150
UNIT WEIGHT OF WATER (pcf)=	62.4

PIMA ROAD THREE BASINS (PIMA2REV.108B)

RESULTS OF ANALYSIS

MOMENTS AT LOCATIONS IN PIPE CROSS SECTION

LOCATION (deg from crown)	MOMENT MARSTON (in-lbs/in)	MOMENT LATERAL (in-lbs/in)	MOMENT DEAD (in-lbs/in)	MOMENT LIVE (in-lbs/in)	MOMENT WATER (in-lbs/in)
.0	778	-8895	1097	11878	1405
45.0	-3	-989	101	-62	174
90.0	-785	10114	-1262	-12002	-1575
135.0	-3	884	-113	-62	-291
180.0	778	-11545	1403	11878	2340

RING THRUSTS AT LOCATIONS IN PIPE CROSS SECTION

LOCATION (deg from crown)	THRUST MARSTON (lbs/in)	THRUST LATERAL (lbs/in)	THRUST DEAD (lbs/in)	THRUST LIVE (lbs/in)	THRUST WATER (lbs/in)
.0	0	-484	9	0	78
45.0	-25	-295	-23	-402	57
90.0	-52	0	-84	-805	27
135.0	-25	-390	-60	-402	90
180.0	0	-887	-8	0	176

SHEARS AT LOCATIONS IN PIPE CROSS SECTION

LOCATION (deg from crown)	SHEAR MARSTON (lbs/in)	SHEAR LATERAL (lbs/in)	SHEAR DEAD (lbs/in)	SHEAR LIVE (lbs/in)	SHEAR WATER (lbs/in)
.0	0	0	0	0	0
45.0	-25	390	-35	524	-44
90.0	0	903	-8	171	-13
135.0	26	1077	48	-615	61
180.0	0	0	0	-1611	34

PIMA ROAD THREE BASINS (PIMA2REV.108B)

TOTALS (without water loading)

LOCATION (deg)	MOMENT (in/lbs/in)	THRUST (lbs/in)	SHEAR (lbs/in)
.0	4857	-475	0
45.0	-956	-748	852
90.0	-3938	-943	1065
135.0	703	-880	536
180.0	2514	-896	-1611

STRESSES (p.s.i.) - without head & water Load
Tension (+); Compression (-)

LOCATION	OD FIBER	SAFETY FACTOR	ID FIBER	SAFETY FACTOR
.0	-316	9.45	211	2.33
45.0	-17	169.28	-121	24.62
90.0	131	3.77	-297	10.07
135.0	-122	24.32	-46	64.11
180.0	-225	13.26	47	10.41

MINIMUM FACTOR OF SAFETY= 2.33

STRESSES (p.s.i.) - with head & water load
Tension (+); Compression (-)

LOCATION	OD FIBER	SAFETY FACTOR	ID FIBER	SAFETY FACTOR
.0	-388	7.72	293	1.68
45.0	-21	135.95	-106	27.97
90.0	222	2.22	-378	7.93
135.0	-97	30.49	-53	55.97
180.0	-340	8.81	188	2.63

MINIMUM FACTOR OF SAFETY= 1.68

TERRAIN ENGINEERING INC.

6940 Tremont Rd

Dixon, CA 95620

CAST-IN-PLACE EARTH REINFORCED CONCRETE PIPE

STRUCTURAL ANALYSIS

CAPLCOP v. 1.04

TITLE: PIMA ROAD THREE BASINS (PIMA2REV108C)
LOCATION: SCOTTSDALE, AZ
DATE: 4- 6-1998
TIME: 15:26

PIPE DATA	
NOMINAL DIAMETER (in)=	108
MIN. WALL THICKNESS (in)=	10.5
X-SECT. MIN AREA (in**2)=	3909
MOMENT OF INTERIA (in**4)=	96.5
AREA FOR STRESS CALC (in**2)=	10.5
DISTANCE FROM MID-SEC TO NA (in)=	.2

LIVE LOAD DATA	
DESCRIPTION=	HS20
POINT LOAD (LBS)=	16000.0
SOIL DISTRIBUTION=	7.00 ACROSS
=	8.00 DOWN
UNIFORM LOAD ON THE PIPE (psi)=	4.0
WIDTH OF UNIFORM LOAD (in)=	63.0

SOIL DATA	
TRENCH HEIGHT (ft)=	3.0
TOTAL COVER HEIGHT (ft)=	3.0
UNIT WEIGHT OF FILL SOIL (pcf)=	120
UNIT WEIGHT OF IN-SITU SOIL (pcf)=	115
RANKINE COEFFICIENT OF IN-SITU SOIL=	.5
MARSTON LOAD (psi)=	2.6

MISC DATA	
CONCRETE STRENGTH (psi)=	3000
MODULUS RUPTURE (psi)=	493
WATER HEIGHT OVER PIPE CROWN (ft)=	.0
UNIT WEIGHT OF CONCRETE (pcf)=	150
UNIT WEIGHT OF WATER (pcf)=	62.4

PIMA ROAD THREE BASINS (PIMA2REV108C)

RESULTS OF ANALYSIS

MOMENTS AT LOCATIONS IN PIPE CROSS SECTION

LOCATION (deg from crown)	MOMENT MARSTON (in-lbs/in)	MOMENT LATERAL (in-lbs/in)	MOMENT DEAD (in-lbs/in)	MOMENT LIVE (in-lbs/in)	MOMENT WATER (in-lbs/in)
.0	2283	-2725	1097	3519	1405
45.0	-11	-228	101	-18	174
90.0	-2306	2996	-1262	-3556	-1575
135.0	-11	197	-113	-18	-291
180.0	2283	-3328	1403	3519	2340

RING THRUSTS AT LOCATIONS IN PIPE CROSS SECTION

LOCATION (deg from crown)	THRUST MARSTON (lbs/in)	THRUST LATERAL (lbs/in)	THRUST DEAD (lbs/in)	THRUST LIVE (lbs/in)	THRUST WATER (lbs/in)
.0	0	-157	9	0	78
45.0	-76	-90	-23	-118	57
90.0	-154	0	-84	-238	27
135.0	-76	-111	-60	-118	90
180.0	0	-248	-8	0	176

SHEARS AT LOCATIONS IN PIPE CROSS SECTION

LOCATION (deg from crown)	SHEAR MARSTON (lbs/in)	SHEAR LATERAL (lbs/in)	SHEAR DEAD (lbs/in)	SHEAR LIVE (lbs/in)	SHEAR WATER (lbs/in)
.0	0	0	0	0	0
45.0	-76	132	-35	155	-44
90.0	0	300	-8	51	-13
135.0	77	335	48	-182	61
180.0	0	0	0	-477	34

PIMA ROAD THREE BASINS (PIMA2REV108C)

TOTALS (without water loading)

LOCATION (deg)	MOMENT (in/lbs/in)	THRUST (lbs/in)	SHEAR (lbs/in)
.0	4173	-148	0
45.0	-158	-310	173
90.0	-4130	-478	342
135.0	53	-370	279
180.0	3877	-257	-477

STRESSES (p.s.i.) - without head & water Load
Tension (+); Compression (-)

LOCATION	OD FIBER	SAFETY FACTOR	ID FIBER	SAFETY FACTOR
.0	-247	12.10	206	2.39
45.0	-20	144.52	-37	78.86
90.0	186	2.65	-263	11.37
135.0	-37	78.43	-31	92.31
180.0	-241	12.41	180	2.74

MINIMUM FACTOR OF SAFETY= 2.39

STRESSES (p.s.i.) - with head & water load
Tension (+); Compression (-)

LOCATION	OD FIBER	SAFETY FACTOR	ID FIBER	SAFETY FACTOR
.0	-318	9.40	288	1.71
45.0	-24	119.51	-22	127.93
90.0	277	1.78	-343	8.71
135.0	-12	225.30	-38	76.33
180.0	-355	8.42	321	1.54

MINIMUM FACTOR OF SAFETY= 1.54

TERRAIN ENGINEERING INC.

6940 Tremont Rd

Dixon, CA 95620

CAST-IN-PLACE EARTH REINFORCED CONCRETE PIPE

STRUCTURAL ANALYSIS

CAPLCOP v. 1.04

TITLE: PIMA ROAD THREE BASINS (PIMA3ALT96)
LOCATION: SCOTTSDALE, AZ
DATE: 4- 5-1998
TIME: 14:26

PIPE DATA	
NOMINAL DIAMETER (in)=	96
MIN. WALL THICKNESS (in)=	9.0
X-SECT. MIN AREA (in**2)=	2969
MOMENT OF INTERIA (in**4)=	60.8
AREA FOR STRESS CALC (in**2)=	9.0
DISTANCE FROM MID-SEC TO NA (in)=	.1

LIVE LOAD DATA	
DESCRIPTION=	HS20
POINT LOAD (LBS)=	16000.0
SOIL DISTRIBUTION=	7.00 ACROSS
=	8.00 DOWN
UNIFORM LOAD ON THE PIPE (psi)=	1.5
WIDTH OF UNIFORM LOAD (in)=	105.0

SOIL DATA	
TRENCH HEIGHT (ft)=	3.0
TOTAL COVER HEIGHT (ft)=	5.0
UNIT WEIGHT OF FILL SOIL (pcf)=	120
UNIT WEIGHT OF IN-SITU SOIL (pcf)=	115
RANKINE COEFFICIENT OF IN-SITU SOIL=	.5
MARSTON LOAD (psi)=	4.2

MISC DATA	
CONCRETE STRENGTH (psi)=	3000
MODULUS RUPTURE (psi)=	493
WATER HEIGHT OVER PIPE CROWN (ft)=	.0
UNIT WEIGHT OF CONCRETE (pcf)=	150
UNIT WEIGHT OF WATER (pcf)=	62.4

PIMA ROAD THREE BASINS (PIMA3ALT96)

RESULTS OF ANALYSIS

MOMENTS AT LOCATIONS IN PIPE CROSS SECTION

LOCATION (deg from crown)	MOMENT MARSTON (in-lbs/in)	MOMENT LATERAL (in-lbs/in)	MOMENT DEAD (in-lbs/in)	MOMENT LIVE (in-lbs/in)	MOMENT WATER (in-lbs/in)
.0	2894	-2537	738	995	975
45.0	-13	-160	68	-4	120
90.0	-2922	2721	-849	-1004	-1094
135.0	-13	135	-75	-4	-199
180.0	2894	-2956	945	995	1613

RING THRUSTS AT LOCATIONS IN PIPE CROSS SECTION

LOCATION (deg from crown)	THRUST MARSTON (lbs/in)	THRUST LATERAL (lbs/in)	THRUST DEAD (lbs/in)	THRUST LIVE (lbs/in)	THRUST WATER (lbs/in)
.0	0	-171	7	0	61
45.0	-110	-95	-17	-37	44
90.0	-221	0	-63	-75	21
135.0	-110	-112	-45	-37	71
180.0	0	-243	-6	0	138

SHEARS AT LOCATIONS IN PIPE CROSS SECTION

LOCATION (deg from crown)	SHEAR MARSTON (lbs/in)	SHEAR LATERAL (lbs/in)	SHEAR DEAD (lbs/in)	SHEAR LIVE (lbs/in)	SHEAR WATER (lbs/in)
.0	0	0	0	0	0
45.0	-110	148	-27	50	-34
90.0	0	333	-6	16	-10
135.0	111	357	37	-57	48
180.0	0	0	0	-151	26

PIMA ROAD THREE BASINS (PIMA3ALT96)

TOTALS (without water loading)

LOCATION (deg)	MOMENT (in/lbs/in)	THRUST (lbs/in)	SHEAR (lbs/in)
.0	2089	-165	0
45.0	-112	-262	59
90.0	-2055	-361	342
135.0	39	-307	446
180.0	1877	-250	-151

STRESSES (p.s.i.) - without head & water Load
Tension (+); Compression (-)

LOCATION	OD FIBER	SAFETY FACTOR	ID FIBER	SAFETY FACTOR
.0	-177	16.89	132	3.74
45.0	-20	145.69	-36	80.49
90.0	116	4.23	-187	15.94
135.0	-36	80.64	-30	95.52
180.0	-170	17.55	107	4.60

MINIMUM FACTOR OF SAFETY= 3.74

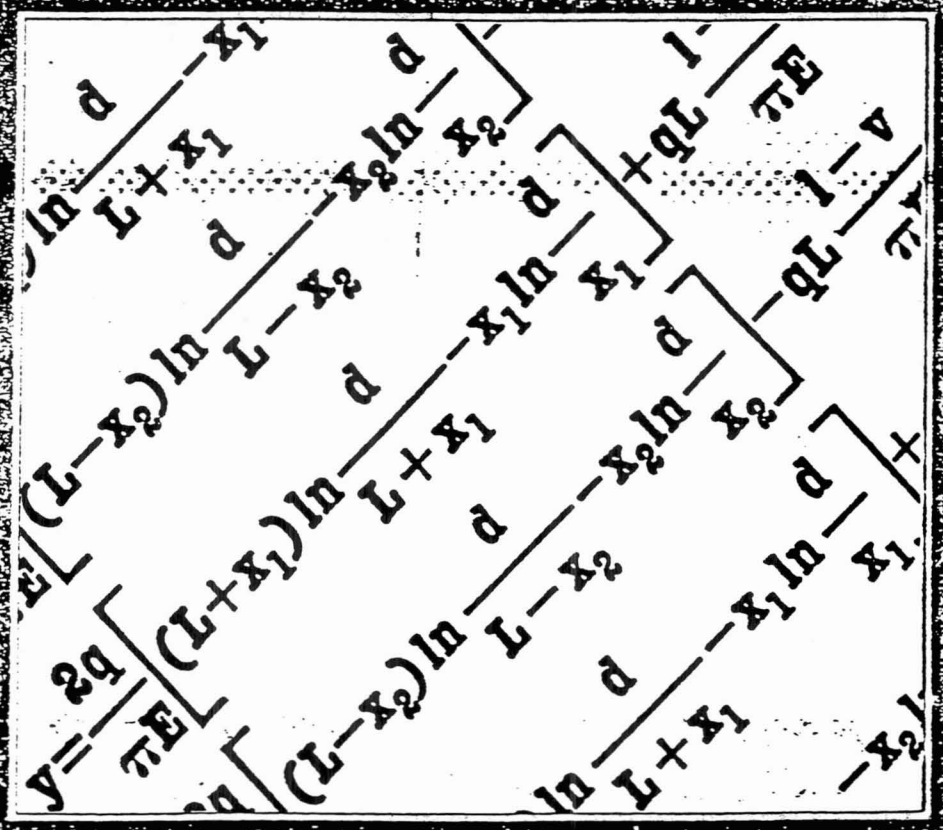
STRESSES (p.s.i.) - with head & water load
Tension (+); Compression (-)

LOCATION	OD FIBER	SAFETY FACTOR	ID FIBER	SAFETY FACTOR
.0	-244	12.24	209	2.36
45.0	-24	121.11	-23	126.51
90.0	202	2.44	-264	11.34
135.0	-13	212.79	-37	79.23
180.0	-277	10.77	239	2.07

MINIMUM FACTOR OF SAFETY= 2.07

Sixth Edition

Roark's Formulas for Stress & Strain



Warren C. Young

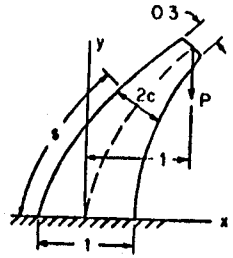


Figure 8.8

in Fig. 8.8. The vertical deflection at the loaded end is desired. To keep the use of specific dimensions to a minimum let the depth of the curved beam at the fixed end = 1.0, the thickness = 0.5, and the horizontal location of the load $P = 1.0$. The beam will be subdivided into eight segments, each spanning 0.25 units in the y direction. Normally a constant length along the span is used, but using constant Δy gives shorter spans where moments are larger and curvatures are sharper. The numerical calculations are also easier. Use will be made of the following expressions in order to provide the tabulated information from which the needed summation can be found. Note that y_i and x_i are used here as the y and x positions of the midlength of each segment.

$$x = 0.25y^2 \qquad \frac{dx}{dy} = 0.5y \qquad \frac{d^2x}{d^2y} = 0.5 \qquad \Delta l = \Delta y(1 + x_i)^{1/2}$$

$$R = \frac{[1 + (dx/dy)^2]^{3/2}}{d^2x/d^2y}$$

$$\frac{h}{c} = \frac{R}{c} - \frac{2}{\ln[(R/c + 1)/(R/c - 1)]} \quad \text{for } \frac{R}{2c} < 8 \quad \text{[see Eq. (1) and case 1 of Table 16]}$$

or

$$\frac{h}{c} = \frac{I_c}{RAc} = \frac{t(2c)^3}{12(Rt2c^2)} = \frac{c}{3R} \quad \text{for } \frac{R}{2c} > 8 \quad \text{[see Eq. (3)]}$$

The desired vertical deflection of the loaded end can be determined from Castigliano's theorem, using Eq. (9) for U_f in summation form rather than integral form. This reduces to

$$\delta = \frac{\delta U}{\delta P} = \frac{P}{E}\sum\left[\frac{(M/P)^2}{hR} + F\left(\frac{V}{P}\right)^2 2(1+\nu) + \left(\frac{N}{P}\right)^2 - 2\frac{M}{P}\frac{N}{P}\right]\frac{\Delta l}{A}$$

$$= \frac{P}{E}\sum\frac{\Delta l}{A}[B]$$

where $[B]$ and $[B]\Delta l/A$ are the last two columns in the table. The internal forces and moments can be determined from equilibrium equations as

$$\frac{M}{P} = -(1 - x_i) \qquad \theta_i = \tan^{-1}\frac{dx}{dy} \qquad V = P\sin\theta_i \qquad \text{and} \qquad N = -P\cos\theta_i$$

In the evaluation of the above equations for this problem, $F = 1.2$ and $\nu = 0.3$. In the table below one must fill in the first five columns in order to find the total length of the beam before the midsegment depth 2c can be found and the table completed.

Element no.	y_i	x_i	R	Δl	c	R/c
1	0.125	0.004	2.012	0.251	0.481	4.183
2	0.375	0.035	2.106	0.254	0.442	4.761
3	0.625	0.098	2.300	0.262	0.403	5.707
4	0.875	0.191	2.601	0.273	0.362	7.180
5	1.125	0.316	3.020	0.287	0.320	9.451
6	1.375	0.473	3.574	0.303	0.275	13.019
7	1.625	0.660	4.278	0.322	0.227	18.860
8	1.875	0.879	5.151	0.343	0.176	29.243
				2.295		

Element no.	h/c	M/P	V/P	N/P	$[B]$	$[B]\frac{\Delta l}{A}$
1	0.0809	−0.996	0.062	−0.998	11.695	6.092
2	0.0709	−0.965	0.184	−0.983	13.269	7.627
3	0.0589	−0.902	0.298	−0.954	14.370	9.431
4	0.0467	−0.809	0.401	−0.916	14.737	11.101
5	0.0354	−0.684	0.490	−0.872	14.007	12.569
6	0.0256	−0.527	0.567	−0.824	11.856	13.105
7	0.0177	−0.340	0.631	−0.776	8.049	11.431
8	0.0114	−0.121	0.684	−0.730	3.232	6.290
						77.555

Therefore, the deflection at the load and in the direction of the load is $77.56P/E$ in whatever units are chosen as long as the depth at the fixed end is unity. If one maintains the same length-to-depth ratio and the same shape, the deflection can be expressed as $\delta = 77.56P/(E2t_o)$, where t_o is the constant thickness of the beam.

Michael Plesha (Ref. 33) provided a finite-element solution for this configuration and obtained for the load point a vertically downward deflection of 72.4 units and a horizontal deflection of 88.3 units. The 22 elements he used were nine-node, quadratic displacement, Lagrange elements. The reader is invited to apply a horizontal dummy load and verify the horizontal deflection.

8.3 Circular Rings and Arches

In large pipelines, tanks, aircraft, and submarines the circular ring is an important structural element, and for correct design it is often necessary to calculate the stresses and deflections produced in such a ring under various conditions of loading and support. The circular arch of uniform section is often employed in buildings, bridges, and machinery.

Rings. A closed circular ring may be regarded as a *statically indeterminate beam* and analyzed as such by the use of Castigliano's second

theorem. In Table 17 are given formulas thus derived for the bending moments, tensions, shears, horizontal and vertical deflections, and rotations of the load point in the plane of the ring for various loads and supports. By superposition, these formulas can be combined so as to cover almost any condition of loading and support likely to occur.

The ring formulas are based on the following assumptions: (1) The ring is of uniform cross section and has symmetry about the plane of curvature. An exception to this requirement of symmetry can be made if moment restraints are provided to prevent rotation of each cross section out of its plane of curvature. Lacking the plane of symmetry and any external constraints, out-of-plane deformations will accompany in-plane loading. Meck, in Ref. 21, derives expressions concerning the coupling of in-plane and out-of-plane deformations of circular rings of arbitrary compact cross section and resulting instabilities. (2) All loadings are applied at the radial position of the centroid of the cross section. For thin rings this is of little concern, but for radially thick rings a concentrated load acting in other than a radial direction and not at the centroidal radius must be replaced by a statically equivalent load at the centroidal radius and a couple. For case 15, where the loading is due to gravity or a constant linear acceleration, and for case 21, where the loading is due to rotation around an axis normal to the plane of the ring, the proper distribution of loading through the cross section is accounted for in the formulas. (3) It is nowhere stressed beyond the elastic limit. (4) It is not so severely deformed as to lose its essentially circular shape. (5) Its deflection is due primarily to bending, but for thicker rings the deflections due to deformations caused by axial tension or compression in the ring and/or by transverse shear stresses in the ring may be included. To include these effects, we can evaluate first the coefficients α and β, the *axial stress deformation factor*, and the *transverse shear deformation factor*, and then the constants k_1 and k_2. Such corrections are more often necessary when composite or sandwich construction is employed. If no axial or shear stress corrections are desired, α and β are set equal to zero and the values of k are set equal to unity. (6) In the case of pipes acting as beams between widely spaced supports, the distribution of shear stress across the section of the pipe is in accordance with Art. 7.1, Eq. (2), and the direction of the resultant shear stress at any point of the cross section is tangential.

Note carefully the deformations given regarding the point or points of loading as compared with the deformations of the horizontal and vertical diameters. For many of the cases listed, the numerical values of load and deflection coefficients have been given for several positions of the loading. These coefficients do not include the effect of axial and shear deformation.

No account has been taken in Table 17 of the effect of radial stresses in the vicinity of the concentrated loads. These stresses and the local deformations they create can have a significant effect on overall ring deformations and peak stresses. In case 1 a reference is made to Art. 13.3 in which thick-walled rollers or rings are loaded on the outer ends of a diameter. The stresses and deflections given here are different from those predicted by the equations in case 1. If a concentrated load is used only for purposes of superposition, as is often the case, there is no cause for concern, but if an actual applied load is concentrated over a small region and the ring is sharply curved with thick walls, then one must be aware of the possible errors.

EXAMPLES

1. A pipe with a diameter of 13 ft and thickness of $\frac{1}{2}$ in is supported at intervals of 44 ft by rings, each ring being supported at the extremities of its horizontal diameter by vertical reactions acting at the centroids of the ring sections. It is required to determine the bending moments in a ring at the bottom, sides, and top, and the maximum bending moment when the pipe is filled with water.

Solution. We use the formulas for cases 4 and 20. Taking the weight of the water as 62.4 lb/ft³ and the weight of the shell as 20.4 lb/ft², the total weight W of 44 ft of pipe carried by one ring is found to be 401,100 lb. Therefore, for case 20, $W = 401{,}100$; and for case 4, $W = 200{,}550$ and $\theta = \pi/2$. Assume a thin ring, $\alpha = \beta = 0$.

At bottom:

$$M = M_C = 0.2387(401{,}100)(6.5)(12) - 0.50(200{,}550)(78)$$
$$= 7.468(10^6) - 7.822(10^6) = -354{,}000 \text{ in-lb}$$

At top:

$$M = M_A = 0.0796(401{,}100)(78) - 0.1366(200{,}550)(78) = 354{,}000 \text{ in-lb}$$
$$N = N_A = 0.2387(401{,}100) - 0.3183(200{,}550) = 31{,}900 \text{ lb}$$
$$V = V_A = 0$$

At sides:

$$M = M_A - N_A R(1 - u) + V_A R z + LT_M$$

where for $x = \pi/2$, $u = 0$ $z = 1$, and $LT_M = (WR/\pi)(1 - u - xz/2) = [401{,}100(78)/\pi](1 - \pi/4) = 2.137(10^6)$ for case 20, and $LT_M = 0$ for case 4 since $z - s = 0$. Therefore

$$M = 354{,}000 - 31{,}900(78)(1 - 0) + 0 + 2.137(10^6) = 2800 \text{ in-lb}$$

The value of 2800 is due to the small differences in large numbers used in the superposition. An exact solution would give zero for this value. It is apparent that at least four digits must be carried.

To determine the location of maximum bending moment let $0 < x < \pi/2$ and

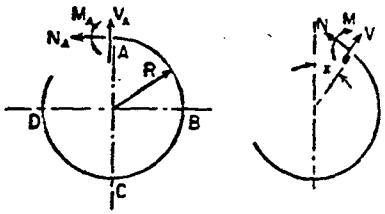
(text continues on p. 282)

TABLE 17 Formulas for circular rings

NOTATION: W = load (force); w and z = unit loads (force per unit of circumferential length); ρ = unit weight of contained liquid (force per unit volume); M_o = applied couple (force-length). M_A, M_B, M_C, and M are internal moments at A, B, C, and x, respectively, positive as shown. N_A, N, V_A, and V are internal forces, positive as shown. E = modulus of elasticity (force per unit area); ν = Poisson's ratio; A = cross-sectional area (length squared); R = radius to the centroid of the cross section (length); I = area moment of inertia of ring cross section about the principal axis perpendicular to the plane of the ring (length^4). [Note that for a pipe or cylinder, a representative segment of unit axial length may be used by replacing EI by $Et^3/12(1-\nu^2)$.] h = positive distance measured radially inward from the centroidal axis of the cross section to the neutral axis of pure bending (see Art. 8.1). θ, x, and ϕ are angles (radians) and are limited to the range zero to π for all cases except 18 and 19; $s = \sin\theta$, $c = \cos\theta$, $z = \sin x$, $u = \cos x$, $n = \sin\phi$, and $e = \cos\phi$.

D_V and D_H are changes in the vertical and horizontal diameters, respectively, and an increase is positive. ΔL is the change in the lower half of the vertical diameter or the vertical motion relative to point C of a line connecting points B and D on the ring. Similarly ΔL_H is the vertical motion relative to point C of a horizontal line connecting the load points on the ring. D_{HW} is the change in length of a horizontal line connecting the load points on the ring. ψ is the angular rotation (radians) of the load point in the plane of the ring and is positive in the direction of positive θ. For the distributed loadings the load points just referred to are the points where the distributed loading starts, i.e., the position located by the angle θ. The reference to points A, B, and C and to the diameters refer to positions on a circle of radius R passing through the centroids of the several sections; i.e., diameter = $2R$. It is important to consider this when dealing with thick rings. Similarly, all concentrated and distributed loadings are assumed to be applied at the radial position of the centroid with the exception of the cases where the ring is loaded by its own weight or by dynamic loading, cases 15 and 21. In these two cases the actual radial distribution of load is considered. If the loading is on the outer or inner surfaces of thick rings, an equivalent loading at the centroidal radius R must be used. See the examples to determine how this might be accomplished.

The hoop-stress deformation factor is $\alpha = I/AR^2$ for thin rings or $\alpha = h/R$ for thick rings. The transverse (radial) shear deformation factor is $\beta = FEI/GAR^2$ for thin rings or $\beta = 2F(1+\nu)h/R$ for thick rings, where G is the shear modulus of elasticity and F is a shape factor for the cross section (see Art. 7.10). The following constants are defined to simplify the expressions which follow. Note that these constants are unity if no correction for hoop stress or shear stress is necessary or desired for use with thin rings. $k_1 = 1 - \alpha + \beta$, $k_2 = 1 - \alpha$.



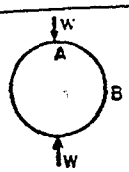
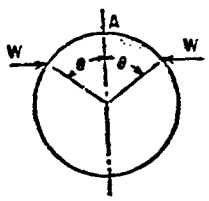
General formulas for moment, hoop load, and radial shear

$$M = M_A - N_A R(1-u) + V_A R z + LT_M$$
$$N = N_A u + V_A z + LT_N$$
$$V = -N_A z + V_A u + LT_V$$

where LT_M, LT_N, and LT_V are load terms given below for several types of load

Note: Due to symmetry in most of the cases presented, the loads beyond 180° are not included in the load terms. Only for cases 16, 17, and 19 should the equations for M, N, and V be used beyond 180°.

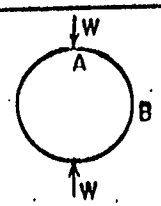
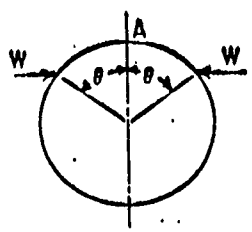
Note: The use of the bracket $\langle x-\theta\rangle^n$ is explained on page 98 and has a value of zero unless $x > \theta$

Reference no., loading, and load terms	Formulas for moments, loads, and deformations and some selected numerical values
1.  $LT_M = \frac{-WRz}{2}$ $LT_N = \frac{-Wz}{2}$ $LT_V = \frac{-Wu}{2}$	$M_A = \frac{WRk_2}{\pi}$ $N_A = 0$ $V_A = 0$ $D_H = \frac{WR^3}{EI}\left(\frac{k_1}{2} - k_2 + \frac{2k_2^2}{\pi}\right)$ $D_V = \frac{-WR^3}{EI}\left(\frac{\pi k_1}{4} - \frac{2k_2^2}{\pi}\right)$ Max $+M = M_A = 0.3183WRk_2$ Max $-M = M_B = -(0.5 - 0.3183k_2)WR$ If $\alpha = \beta = 0$, $D_H = 0.1366\frac{WR^3}{EI}$ and $D_V = -0.1488\frac{WR^3}{EI}$ *Note:* For concentrated loads on thick-walled rings, study the material in Art. 13.3 on hollow pins and rollers. Radial stresses under the concentrated loads have a significant effect not considered here.
2.  $LT_M = -WR(c-u)\langle x-\theta\rangle^0$ $LT_N = Wu\langle x-\theta\rangle^0$ $LT_V = -Wz\langle x-\theta\rangle^0$	$M_A = \frac{-WR}{\pi}[\pi - \theta(1-c) - s(k_2 - c)]$ $M_C = \frac{-WR}{\pi}[\theta(1+c) - s(k_2 + c)]$ $N_A = \frac{-W}{\pi}[\pi - \theta + u]$ $V_A = 0$ $D_H = \begin{cases} \frac{-WR^3}{EI\pi}[0.5\pi k_1\theta - \pi c) + 2k_2\theta c - 2k_2^2 s] & \text{if } \theta \le \frac{\pi}{2} \\ \frac{-WR^3}{EI\pi}[0.5\pi k_1(\pi - \theta + sc) - 2k_2(\pi - \theta)c - 2k_2^2 s] & \text{if } \theta \ge \frac{\pi}{2} \end{cases}$ $D_V = \frac{WR^3}{EI}\left[\frac{k_1 s^2}{2} - k_2\left(1 - c + \frac{2\theta c}{\pi}\right) + \frac{2k_2^2 s}{\pi}\right]$ $\Delta L = \begin{cases} \frac{WR^3}{EI}\left[\frac{\theta c}{2} + \frac{k_1\theta - \pi c}{2\pi} - k_2\left(\frac{\theta c}{\pi} + \frac{s}{2}\right) + \frac{k_2^2 s}{\pi}\right] & \text{if } \theta \le \pi/2 \\ \frac{WR^3}{EI}\left[\frac{\pi - \theta c}{2} + \frac{k_1\theta - \pi c - \pi c^2}{2\pi} - k_2\left(1 + \frac{\theta c}{\pi} - \frac{s}{2}\right) + k_2^2 s/\pi\right] & \text{if } \theta \ge \pi/2 \end{cases}$ $\Delta L_H = \frac{WR^3}{EI\pi}[\pi - \theta - \theta c + 0.5k_1 s^2\theta - \pi c + k_2(2\theta c^2 - \pi c^2 - \theta c - \theta) + k_2^2 s(1+c)]$ $D_{HW} = \frac{-WR^3}{EI\pi}[\pi - \theta - 2\theta c^2 - k_1\pi c + \pi c^2 - 2\theta c - \pi\theta + \theta^2 - 2k_2\pi(\pi - 2\theta) - 2k_2^2 s^2]$ $\Delta\psi = \frac{-WR^2}{EI\pi}[\pi - \theta - \theta c - k_1\pi c + \pi - 2\theta]$ Max $+M = \frac{WRs(k_2 - c^2)}{\pi}$ at $x = \theta$ Max $-M = \begin{cases} M_A & \text{if } \theta \le \frac{\pi}{2} \\ M_C & \text{if } \theta \ge \frac{\pi}{2} \end{cases}$ If $\alpha = \beta = 0$, $M = K_M WR$, $N = K_N W$, $D = K_D WR^3/EI$, $\Delta\psi = K_{\Delta\psi} WR^2/EI$, etc.

θ	30	45°	60°
K_{MA}	−0.0903	−0.1538	−0.1955
K_{MC}	0.0398	0.1125	0.2068
K_{NA}	−0.9712	−0.9092	−0.8045
K_{DH}	−0.0157	−0.0461	−0.0891
K_{DV}	0.0207	0.0537	0.0930
$K_{\Delta L}$	0.0060	0.0179	0.0355
$K_{\Delta L_H}$	0.0119	0.0247	0.0391
K_{DHW}	−0.0060	−0.0302	−0.0770
$K_{\Delta\psi}$	0.0244	0.0496	0.0590

Note: Due to symmetry in [illegible] of the [illegible] the l[illegible] beyon[illegible] are [illegible]cludi[illegible]e lo[illegible]ns. C[illegible]r cas[illegible]17, [illegible] and 19 should the equations for M, N, an[illegible]e used beyond 180°.

Note: The use of the bracket $\langle x - \theta \rangle^0$ is explained on page 98 and has a value of zero unless $x > \theta$

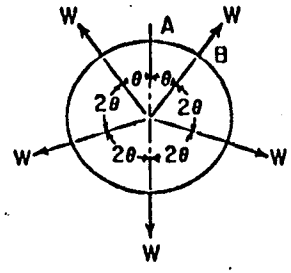
Reference no., loading, and load terms	Formulas for moments, loads, and deformations and some selected numerical values
1.  $LT_M = \dfrac{-WRz}{2}$ $\quad LT_N = \dfrac{-Wz}{2}$ $LT_v = \dfrac{-Wu}{2}$	$M_A = \dfrac{WRk_2}{\pi}$ $N_A = 0$ $V_A = 0$ $D_H = \dfrac{WR^3}{EI}\left(\dfrac{k_1}{2} - k_2 + \dfrac{2k_2^2}{\pi}\right)$ $D_V = \dfrac{-WR^3}{EI}\left(\dfrac{\pi k_1}{4} - \dfrac{2k_2^2}{\pi}\right)$ Max $+M = M_A = 0.3183WRk_2$ Max $-M = M_B = -(0.5 - 0.3183k_2)WR$ If $\alpha = \beta = 0$, $D_H = 0.1366\dfrac{WR^3}{EI}$ and $D_V = -0.1488\dfrac{WR^3}{EI}$ *Note:* For concentrated loads on thick-walled rings, study the material in Art. 13.3 on hollow pins and rollers. Radial stresses under the concentrated loads have a significant effect not considered here.
2.  $LT_M = -WR(c - u)\langle x - \theta \rangle^0$ $LT_N = Wu\langle x - \theta \rangle^0$ $LT_V = -Wz\langle x - \theta \rangle^0$	$M_A = \dfrac{-WR}{\pi}[(\pi - \theta)(1 - c) - s(k_2 - c)]$ $M_C = \dfrac{-WR}{\pi}[\theta(1 + c) - s(k_2 + c)]$ $N_A = \dfrac{-W}{\pi}[\pi - \theta + sc]$ $V_A = 0$ $D_H = \begin{cases} \dfrac{-WR^3}{EI\pi}[0.5\pi k_1(\theta - sc) + 2k_2\theta c - 2k_2^2 s] & \text{if } \theta \le \dfrac{\pi}{2} \\ \dfrac{-WR^3}{EI\pi}[0.5\pi k_1(\pi - \theta + sc) - 2k_2(\pi - \theta)c - 2k_2^2 s] & \text{if } \theta \ge \dfrac{\pi}{2} \end{cases}$ $D_V = \dfrac{WR^3}{EI}\left[\dfrac{k_1 s^2}{2} - k_2\left(1 - c + \dfrac{2\theta c}{\pi}\right) + \dfrac{2k_2^2 s}{\pi}\right]$ $\Delta L = \begin{cases} \dfrac{WR^3}{EI}\left[\dfrac{\theta c}{2} + \dfrac{k_1(\theta - sc)}{2\pi} - k_2\left(\dfrac{\theta c}{\pi} + \dfrac{s}{2}\right) + \dfrac{k_2^2 s}{\pi}\right] & \text{if } \theta \le \pi/2 \\ \dfrac{WR^3}{EI}\left[\dfrac{(\pi - \theta)c}{2} + \dfrac{k_1(\theta - sc - \pi c^2)}{2\pi} - k_2\left(1 + \dfrac{\theta c}{\pi} - \dfrac{s}{2}\right) + k_2^2 s/\pi\right] & \text{if } \theta \ge \pi/2 \end{cases}$ $\Delta L_{1V} = \dfrac{WR^3}{EI\pi}[(\pi - \theta)\theta sc + 0.5k_1 s^2(\theta - sc) + k_2(2\theta s^2 - \pi s^2 - \theta c - \theta) + k_2^2 s(1 + c)]$ $D_{WH} = \dfrac{-WR^3}{EI\pi}[(\pi - \theta)2\theta c^2 - k_1(\pi sc + s^2c^2 - 2\theta sc - \pi\theta + \theta^2) - 2k_2 sc(\pi - 2\theta) - 2k_2^2 s^2]$ $\Delta\psi = \dfrac{-WR^2}{EI\pi}[(\pi - \theta)\theta c - k_2 s(sc + \pi - 2\theta)]$ Max $+M = \dfrac{WRs(k_2 - c^2)}{\pi}$ at $x = \theta$ Max $-M = \begin{cases} M_A & \text{if } \theta \le \dfrac{\pi}{2} \\ M_C & \text{if } \theta \ge \dfrac{\pi}{2} \end{cases}$ If $\alpha = \beta = 0$, $M = K_M WR$, $N = K_N W$, $D = K_D WR^3/EI$, $\Delta\psi = K_{\Delta\psi} WR^2/EI$, etc.

θ	30°	45°	60°
K_{MA}	−0.0903	−0.1538	−0.1955
K_{MC}	0.0398	0.1125	0.2068
K_{NA}	−0.9712	−0.9092	−0.8045
K_{DH}	−0.0157	−0.0461	−0.0891
K_{DV}	0.0207	0.0537	0.0930
$K_{\Delta L}$	0.0060	0.0179	0.0355
$K_{\Delta L,W}$	0.0119	0.0247	0.0391
K_{DWH}	−0.0060	−0.0302	−0.0770
$K_{\Delta\psi}$	0.0244	0.0496	0.0590

TABLE 17 Formulas for circular rings (*Continued*)

Reference no., loading, and load terms	Formulas for moments, loads, and deformations and some selected numerical values

7. Ring under any number of equal radial forces equally spaced



For $0 < x < \theta$ $\quad M = \dfrac{WR(u/s - k_2/\theta)}{2} \quad N = \dfrac{Wu}{2s} \quad V = \dfrac{-Wz}{2s}$

Max $+M = M_A = \dfrac{WR(1/s - k_2/\theta)}{2}$ $\quad$ Max $-M = \dfrac{-WR}{2}\left(\dfrac{k_2}{\theta} - \dfrac{c}{s}\right)$ at each load position

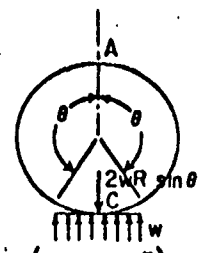
Radial displacement at each load point $= \Delta R_H = \dfrac{WR^3}{EI}\left[\dfrac{k_1(\theta - sc)}{4s^2} + \dfrac{k_2 c}{2s} - \dfrac{k_2^2}{2\theta}\right]$

Radial displacement at $x = 0, 2\theta, \ldots = \Delta R_A = \dfrac{-WR^3}{EI}\left[\dfrac{k_1(s - \theta c)}{4s^2} - \dfrac{k_2}{2s} + \dfrac{k_2^2}{2\theta}\right]$

If $\alpha = \beta = 0$, $M = K_M WR$, $\Delta R = K_{\Delta R} WR^3/EI$

θ	15°	30°	45°	60°	90°
K_{M_A}	0.02199	0.04507	0.07049	0.09989	0.18169
K_{M_H}	−0.04383	−0.08890	−0.13662	−0.18879	−0.31831
$K_{\Delta R_H}$	0.00020	0.00168	0.00608	0.01594	0.07439
$K_{\Delta R_A}$	−0.00018	−0.00148	−0.00539	−0.01426	−0.06831

8.



$\left(\textit{Note: } \theta \geq \dfrac{\pi}{2}\right)$

$I.T_M = \dfrac{-wR^2}{2}(z - s)^2\langle x - \theta\rangle^0$

$I.T_N = -wRz(z - s)\langle x - \theta\rangle^0$

$I.T_V = -wRu(z - s)\langle x - \theta\rangle^0$

$M_A = \dfrac{wR^2}{2\pi}\left[\pi(s^2 - 0.5) - \dfrac{sc - \theta}{2} - s^2\left(\theta + \dfrac{2s}{3}\right) - k_2(2s + sc - \pi + \theta)\right]$

$M_C = \dfrac{-wR^2}{2\pi}\left[\dfrac{\pi}{2} + \dfrac{sc}{2} - \dfrac{\theta}{2} + \theta s^2 - \dfrac{2s^3}{3} + k_2(2s + sc - \pi + \theta)\right]$

$N_A = \dfrac{-wRs^3}{3\pi}$

$V_A = 0$

$D_H = \dfrac{-wR^4}{2EI\pi}\left[\dfrac{k_1\pi s^3}{3} + k_2(\pi - 2\pi s^2 - \theta + 2\theta s^2 + sc) + 2k_2^2(2s + sc - \pi + \theta)\right]$

$D_V = \dfrac{wR^4}{2EI\pi}\left[k_1\pi\left(\pi s - \theta s - \dfrac{2}{3} - c + \dfrac{c^3}{3}\right) - k_2(\pi c^2 + sc - \theta + 2\theta s^2) - 2k_2^2(2s + sc - \pi + \theta)\right]$

$\Delta L = \dfrac{wR^4}{4EI\pi}\left[\pi(\pi - \theta)\dfrac{2s^2 - 1}{2} - \dfrac{\pi sc}{2} - 2\pi k_1\left(\dfrac{2}{3} - \pi s + c + \theta s - \dfrac{c^3}{3} + \dfrac{s^3}{3\pi}\right) - k_2(sc + \pi - \theta + 2\theta s^2 + 2s\pi - \pi^2 + \pi\theta + \pi sc) - 2k_2^2(2s + sc - \pi + \theta)\right]$

Max $+M$ occurs at an angular position x_1 where $x_1 > \theta$, $x_1 > 123.1°$, and

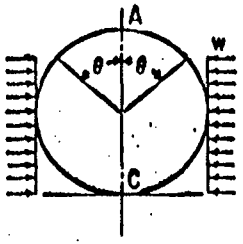
$\tan x_1 + \dfrac{3\pi(s - \sin x_1)}{s^3} = 0$

Max $-M = M_C$

If $\alpha = \beta = 0$, $M = K_M wR^2$, $N = K_N wR$, $D = K_D wR^4/EI$, etc.

θ	90°	120°	135°	150°
K_{M_A}	−0.0494	−0.0329	−0.0182	−0.0065
K_{N_A}	−0.1061	−0.0689	−0.0375	−0.0133
K_{M_C}	−0.3372	−0.2700	−0.1932	−0.1050
K_{D_H}	−0.0533	−0.0362	−0.0204	−0.0074
K_{D_V}	0.0655	0.0464	0.0276	0.0108
$K_{\Delta L}$	0.0448	0.0325	0.0198	0.0080

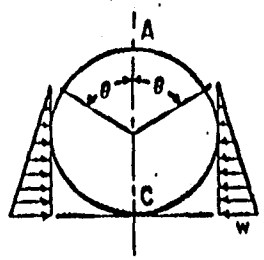
TABLE 17 Formulas for circular rings (*Continued*)

Reference no., loading, and load terms	Formulas for moments, loads, and deformations and some selected numerical values
10.  $I.T_M = \frac{-wR^2}{2}(c-u)^2\langle x-\theta\rangle^0$ $I.T_N = wRu(c-u)\langle x-\theta\rangle^0$ $I.T_V = wRz(c-u)\langle x-\theta\rangle^0$	$M_A = \frac{-wR^2}{4\pi}\left[(\pi-\theta)(4c+2s^2-1)+s\left(4-\frac{4s^2}{3}-c\right)-2k_2(\pi-\theta+sc)\right]$ $M_C = \frac{-wR^2}{4\pi}\left[3\pi+\theta+4\theta c-2\theta s^2-4s-sc+\frac{4s^3}{3}-2k_2(\pi-\theta+sc)\right]$ $N_A = \frac{-wR}{\pi}\left(\pi c+s-\theta c-\frac{s^3}{3}\right)$ $V_A = 0$ $D_H = \begin{cases}\frac{-wR^4}{6EI\pi}\{\pi k_1(s^3+3\theta c+4-3s)+3k_2(\pi-\theta+2\theta c^2-sc)-6k_2^2(\pi-\theta+sc)\} & \text{for } \theta \le \frac{\pi}{2}\\ \frac{-wR^4}{2EI\pi}\left\{\pi k_1\left[c(\pi-\theta)+s-\frac{s^3}{3}\right]+k_2[(\pi-\theta)(2s^2-1)-sc]-2k_2^2(\pi-\theta+sc)\right\} & \text{for } \theta \ge \frac{\pi}{2}\end{cases}$ $D_V = \frac{wR^4}{6EI\pi}\{\pi k_1(2-c^3+3c)+3k_2[2\theta s^2-\theta+sc-\pi(1+2c+s^2)]+6k_2^2(\pi-\theta+sc)\}$ $\Delta L = \begin{cases}\frac{wR^4}{12EI\pi}[1.5\pi(\theta-2\theta s^2-sc)+2k_1(2\pi+s^3+3\theta c-3s)+3k_2(sc+\theta\pi+2\theta s^2-3\pi-\theta-\pi sc)+6k_2^2(\pi-\theta+sc)] & \text{for } \theta \le \frac{\pi}{2}\\ \frac{wR^4}{12EI\pi}\{1.5\pi[(\pi-\theta)(1-2s^2)+sc]+2k_1(2\pi+s^3+3\theta c-3s-\pi c^3) & \\ \qquad +3k_2[(\pi+1)(\pi-\theta+sc)+2\theta s^2-4\pi(1+c)]+6k_2^2(\pi-\theta+sc)\} & \text{for } \theta \ge \frac{\pi}{2}\end{cases}$ Max $+M$ occurs at an angular position x_1 where $x_1 > \theta$, $x_1 > 90°$, and $x_1 = \arccos\frac{s^3/3+\theta c-s}{\pi}$ Max $-M = M_C$ If $\alpha = \beta = 0$, $M = K_M wR^2$, $N = K_N wR$, $D = K_D wR^4/EI$, etc.

θ	0°	30°	45°	60°	90°	120°	135°	150°
K_{MA}	−0.2500	−0.2434	−0.2235	−0.1867	−0.0872	−0.0185	−0.0052	−0.00076
K_{NA}	−1.0000	−0.8676	−0.7179	−0.5401	−0.2122	−0.0401	−0.0108	−0.00155
K_{MC}	−0.2500	−0.2492	−0.2448	−0.2315	−0.1628	−0.0633	−0.0265	−0.00663
K_{DH}	−0.1667	−0.1658	−0.1610	−0.1470	−0.0833	−0.0197	−0.0057	−0.00086
K_{DV}	0.1667	0.1655	0.1596	0.1443	0.0833	0.0224	0.0071	0.00118
$K_{\Delta L}$	0.0833	0.0830	0.0812	0.0756	0.0486	0.0147	0.0049	0.00086

K_{D_H}	−0.1667	−0.1658	−0.1610	−0.1470	−0.0833	−0.0197	−0.0057	−0.00086
K_{D_V}	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
$K_{\Delta L}$	0.0833	0.0830	812	0.0756	0.0486	0.0147	0.0049	0.00086

11.



$$LT_M = \frac{-wR^2}{6(1+c)}(c-u)^3\langle x-\theta\rangle^0$$

$$LT_N = \frac{wRu}{2(1+c)}(c-u)^2\langle x-\theta\rangle^0$$

$$LT_V = \frac{wRz}{2(1+c)}(c-u)^2\langle x-\theta\rangle^0$$

$$M_A = \frac{-wR^2}{(1+c)\pi}\left[(\pi-\theta)\frac{3+12c^2+2c+4cs^2}{24} - \frac{3s^3c-3s-5s^3}{36} + \frac{5sc}{8} - k_2\left(\frac{\pi c}{2} - \frac{\theta c}{2} + \frac{s^3}{3} + \frac{sc^2}{2}\right)\right]$$

$$M_C = \frac{-wR^2}{(1+c)\pi}\left[(\pi-\theta)\frac{-3-12c^2+2c+4cs^2}{24} + \frac{\pi(1+c)^3}{6} + \frac{3s^3c+3s+5s^3}{36} - \frac{5sc}{8} - k_2\left(\frac{\pi c}{2} - \frac{\theta c}{2} + \frac{s^3}{3} + \frac{sc^2}{2}\right)\right]$$

$$N_A = \frac{-wR}{(1+c)\pi}\left[(\pi-\theta)\frac{1+4c^2}{8} + \frac{5sc}{8} - \frac{s^3c}{12}\right]$$

$$V_A = 0$$

$$D_H = \begin{cases} \dfrac{-wR^4}{EI(1+c)\pi}\left\{\pi k_1\left(\dfrac{\theta+40c^2-5sc}{16} + \dfrac{s^3c+16c}{24}\right) - k_2\left(\dfrac{5sc^2+30c+60s^2c-8s}{18} - \dfrac{\pi c}{2}\right) - k_2^2\left[c(\pi-\theta) + \dfrac{2s^3}{3} + sc^2\right]\right\} & \text{for } \theta \le \dfrac{\pi}{2} \\ \dfrac{-wR^4}{EI(1+c)\pi}\left\{\pi k_1\left[(\pi-\theta)\dfrac{1+4c^2}{16} + \dfrac{5sc}{16} - \dfrac{s^3c}{24}\right] - k_2\left[\dfrac{5sc^2-8s}{18} - (\pi-\theta)\dfrac{c+2s^2c}{6}\right] - k_2^2\left[c(\pi-\theta) + s - \dfrac{s^3}{3}\right]\right\} & \text{for } \theta \ge \dfrac{\pi}{2} \end{cases}$$

$$D_V = \frac{wR^4}{EI(1+c)}\left\{k_1\left[\frac{(1+c)^2}{6} - \frac{s^4}{24}\right] + k_2\left(\frac{5sc^2+30c+60s^2c-8s}{18\pi} + \frac{s^2}{2} + \frac{c^3}{6} - c - \frac{2}{3}\right) + k_2^2\frac{c(\pi-\theta)+s-s^3/3}{\pi}\right\}$$

$$\Delta L = \begin{cases} \dfrac{wR^4}{EI(1+c)}\left\{\dfrac{3s+5s^3+60c^3-90c-16}{72} + k_1\left(\dfrac{c}{3} + \dfrac{1}{16} + \dfrac{120c^2+30+2s^3c-15sc}{48\pi}\right) \right. \\ \qquad \left. + k_2\left[\dfrac{1-s^3}{6} - \dfrac{c(3+sc-\theta)}{4} + \dfrac{30c+60s^2c-3s-5s^3}{36\pi}\right] + k_2^2\dfrac{c(\pi-\theta)/2+sc^2/2+s^3/3}{\pi}\right\} & \text{for } \theta \le \dfrac{\pi}{2} \\ \dfrac{wR^4}{EI(1+c)}\left\{\dfrac{-(\pi-\theta)c(1+2s^2)}{24} - \dfrac{sc^2}{24} - \dfrac{s^3}{9} + k_1\left(\dfrac{c}{3} + \dfrac{1}{16} - \dfrac{c^4}{24} + \dfrac{120c^2+30+2s^3c-15sc}{48\pi}\right) \right. \\ \qquad \left. + k_2\left[\dfrac{2s-2+sc^2}{12} + \dfrac{c(\pi-\theta-3-2c)}{4} + \dfrac{30c+60s^2c-3s-5s^3}{36\pi}\right] + k_2^2\dfrac{3c(\pi-\theta)+2s+sc^2}{6\pi}\right\} & \text{for } \theta \ge \dfrac{\pi}{2} \end{cases}$$

Max $+M$ occurs at an angular position x_1 where $x_1 > \theta$, $x_1 > 96.8°$, and

$$x_1 = \arccos\left\{c - \left[(c^2+0.25)\left(1-\frac{\theta}{\pi}\right) + \frac{sc(5-2s^2/3)}{4\pi}\right]^{1/2}\right\}$$

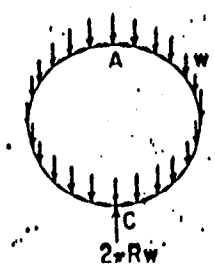
Max $-M = M_C$

If $\alpha = \beta = 0$, $M = K_M wR^2$, $N = K_N wR$, $D = K_D wR^4/EI$, etc.

θ	0°	30°	45°	60°	90°	120°	135°	150°
K_{M_A}	−0.1042	−0.0939	−0.0808	−0.0635	−0.0271	−0.0055	−0.0015	−0.00022
K_{N_A}	−0.3125	−0.2679	−0.2191	−0.1628	−0.0625	−0.0116	−0.0031	−0.00045
K_{M_C}	−0.1458	−0.1384	−0.1282	−0.1129	−0.0688	−0.0239	−0.0096	−0.00232
K_{D_H}	−0.0833	−0.0774	−0.0693	−0.0575	−0.0274	−0.0059	−0.0017	−0.00025
K_{D_V}	0.0833	0.0774	0.0694	0.0579	0.0291	0.0071	0.0022	0.00035
$K_{\Delta L}$	0.0451	0.0424	0.0387	0.0332	0.0180	0.0048	0.0015	0.00026

$$\Delta L = \begin{cases} \dfrac{wR^4}{EI(\pi-\theta)^2}\left\{k_1\left(\dfrac{3s+2\theta-\theta c}{\pi}+\pi-2\theta-\dfrac{\pi s}{2}\right) \right. \\ \qquad + k_2\left[2+s-\theta+\dfrac{\pi^3}{8}+\dfrac{\theta^3}{6}-\dfrac{\theta\pi^2}{4}-(\pi-\theta)^2\right] \\ \qquad \left. + k_2^2\dfrac{(\pi-\theta)^3-6(\pi-\theta-s)}{3\pi}\right\} & \text{for } \theta \le \dfrac{\pi}{2} \\ \dfrac{wR^4}{EI(\pi-\theta)^2}\left\{k_1\left[\dfrac{3s+2\theta-\theta c}{\pi}-s(\pi-\theta)+3c\right] \right. \\ \qquad + k_2\left[\dfrac{(\pi-\theta)^3}{6}-(\pi-\theta)^2-\pi+\theta+s+2+2c\right] \\ \qquad \left. + k_2^2\dfrac{(\pi-\theta)^3-6(\pi-\theta-s)}{3\pi}\right\} & \text{for } \theta \ge \dfrac{\pi}{2} \end{cases}$$

15. Ring supported at base and loaded by own weight per unit length of circumference w



$LT_M = -wR^2[x\xi + K_T(u-1)]$
$LT_N = -wRx\xi$
$LT_V = -wRxu$

$$M_A = wR^2\left[k_2 - 0.5 - \frac{(K_T-1)\beta}{k_1}\right] \qquad \text{where } K_T = 1 + \frac{I}{AR^2}$$

$$M_C = wR^2\left[k_2 + 0.5 + \frac{(K_T-1)\beta}{k_1}\right]$$

$$N_A = wR\left[0.5 + \frac{(K_T-1)k_2}{k_1}\right]$$

$$V_A = 0$$

$$D_H = \frac{wR^3}{EAh}\left(\frac{k_1\pi}{2} - k_2\pi + 2k_2^2\right)$$

$$D_V = \frac{-wR^3}{EAh}\left(\frac{k_1\pi^2}{4} - 2k_2^2\right)$$

$$\Delta L = \frac{-wR^3}{EAh}\left[1 + \frac{3k_1\pi^2}{16} - \frac{k_2\pi}{2} - k_2^2 + (K_T-1)\alpha\right]$$

Note: The constant K_T accounts for the radial distribution of mass in the ring.

Max $+M = M_C$
Max $-M$ occurs at an angular position x_1 where

$$\frac{x_1}{\tan x_1} = -0.5 + \frac{(K_T-1)\beta}{k_1}$$

For a thin ring where $K_T \approx 1$,

$$\text{Max } -M = -wR^2(1.6408 - k_2) \qquad \text{at } x = 105.23°$$

If $\alpha = \beta = 0$,

$$M_A = \frac{wR^2}{2}$$

$$N_A = \frac{wR}{2}$$

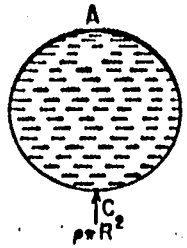
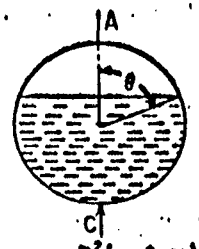
$$D_H = 0.4292\,\frac{wR^4}{EI}$$

$$D_V = -0.4674\,\frac{wR^4}{EI}$$

$$\Delta L = -0.2798\,\frac{wR^4}{EI}$$

$$\text{Max } +M = \tfrac{3}{2}wR^2 \text{ at } C$$

TABLE 17 Formulas for circular rings (*Continued*)

Reference no., loading, and load terms	Formulas for moments, loads, and deformations and some selected numerical values
16. Unit axial segment of pipe filled with liquid of weight per unit volume ρ and supported at the base  $LT_M = \rho R^3\left(1 - u - \frac{\pi\xi}{2}\right)$ $LT_N = \rho R^2\left(1 - u - \frac{\pi\xi}{2}\right)$ $LT_V = \rho R^2\left(\frac{\xi}{2} - \frac{\pi u}{2}\right)$	$M_A = \rho R^3\left(0.75 - \frac{k_2}{2}\right)$ $M_C = \rho R^3\left(1.25 - \frac{k_2}{2}\right)$ $N_A = 0.75\rho R^2$ $V_A = 0$ $D_H = \frac{\rho R^5 12(1-\nu^2)}{Et^3}\left[\frac{k_1\pi}{4} + k_2\left(2 - \frac{\pi}{2}\right) - k_2^2\right]$ $D_V = \frac{-\rho R^5 12(1-\nu^2)}{Et^3}\left(\frac{k_1\pi^2}{8} - 2k_2 + k_2^2\right)$ $\Delta L = \frac{-\rho R^5 12(1-\nu^2)}{Et^3}\left[\frac{k_1 3\pi^2}{32} - k_2\left(0.5 + \frac{\pi}{4}\right) + \frac{k_2^2}{2}\right]$ *Note:* For this case and case 17, $\alpha = \frac{t^2}{12R^2(1-\nu^2)}$ $\beta = \frac{t^2}{6R^2(1-\nu)}$ where t = pipe wall thickness Max $+M = M_C$ Max $-M = -\rho R^3\left(\frac{k_2}{2} - 0.1796\right)$ at $x = 105.23°$ If $\alpha = \beta = 0$, $D_H = 0.2146\,\frac{\rho R^5 12(1-\nu^2)}{Et^3}$ $D_V = -0.2337\,\frac{\rho R^5 12(1-\nu^2)}{Et^3}$ $\Delta L = -0.1399\,\frac{\rho R^5 12(1-\nu^2)}{Et^3}$
17. Unit axial segment of pipe partly filled with liquid of weight per unit volume ρ and supported at the base  	*Note:* see case 16 for expressions for α and β $M_A = \frac{\rho R^3}{4\pi}\{2\theta s^2 + 3s\epsilon - 3\theta + \pi + 2\pi\epsilon^2 + 2k_2[s\epsilon - 2s + (\pi - \theta)(1 - 2\epsilon)]\}$ $N_A = \frac{\rho R^2}{4\pi}[3s\epsilon + (\pi - \theta)(1 + 2\epsilon^2)]$ $V_A = 0$ $D_H = \begin{cases} \frac{\rho R^5 3(1-\nu^2)}{2Et^3\pi}\left\{k_1\pi(s\epsilon + 2\pi - 3\theta + 2\theta\epsilon^2) + 8k_2\pi\left(2\epsilon - s\epsilon - \frac{\pi}{2} + \theta\right) + 8k_2^2[(\pi - \theta)(1 - 2\epsilon) + s\epsilon - 2s]\right\} & \text{for } \theta \le \frac{\pi}{2} \\ \frac{\rho R^5 3(1-\nu^2)}{2Et^3\pi}\{k_1\pi[(\pi - \theta)(1 + 2\epsilon^2) + 3s\epsilon] + 8k_2^2[(\pi - \theta)(1 - 2\epsilon) + s\epsilon - 2s]\} & \text{for } \theta \ge \frac{\pi}{2} \end{cases}$ $D_V = \frac{-\rho R^5 3(1-\nu^2)}{2Et^3\pi}\{k_1\pi[s^2 + (\pi - \theta)(\pi - \theta + 2s\epsilon)] - 4k_2\pi(1 + \epsilon)^2 - 8k_2^2[(\pi - \theta)(1 - 2\epsilon) + s\epsilon - 2s]\}$

$$C_1 = \frac{\rho R^2}{2}(\pi - \theta + sc)$$

$$D_V = \frac{-\rho R^3 3(1-\nu^2)}{2Et^3\pi}\{k_1\pi[s^2 + (\pi-\theta)(\pi-\theta+2sc) \quad 4k_2\pi(1+c)^2 - 8k_2^2[(\pi-\theta)(1-2c)+sc-2s]\}$$

$$LT_M = \frac{\rho R^2}{2}[2c - z(\pi-\theta+sc) - u(1+c^2)]\langle x-\theta\rangle^0$$

$$LT_N = \frac{\rho R^2}{2}[2c - z(\pi-\theta+sc) - u(1+c^2)]\langle x-\theta\rangle^0$$

$$LT_V = \frac{\rho R^2}{2}[zc^2 - u(\pi-\theta+sc)]\langle x-\theta\rangle^0$$

$$\Delta L = \begin{cases} \dfrac{-\rho R^3 3(1-\nu^2)}{2Et^3\pi}\left\{k_1\left[20c^2+\theta-3sc+\pi^2\left(sc-\theta+\dfrac{3\pi}{4}\right)\right]+2k_2\pi[2+20c-2s-4c-\pi+\theta-sc] \right. \\ \qquad\qquad \left. -4k_2^2[(\pi-\theta)(1-2c)+sc-2s]\right\} & \text{for } \theta \le \dfrac{\pi}{2} \\ \dfrac{-\rho R^3 3(1-\nu^2)}{2Et^3\pi}\{k_1[20c^2+\theta-3sc+\pi(\pi-\theta)(\pi-\theta+2sc)-3\pi c^2] \\ \qquad\qquad +2k_2\pi[2s-2(1+c)^2-sc-(\pi-\theta)(1-2c)]-4k_2^2[(\pi-\theta)(1-2c)+sc-2s]\} & \text{for } \theta \ge \dfrac{\pi}{2} \end{cases}$$

$$\text{Max } +M = M_C = \frac{\rho R^3}{4\pi}\{4\pi c + \pi + 20c^2 + \theta - 3sc + 2k_2[(\pi-\theta)(1-2c)+sc-2s]\}$$

Max $-M$ occurs at an angular position x_1 where $x_1' > \theta$, $x_1 > 105.23°$, and x_1 is found from $(\theta + 20c^2 - 3sc - \pi)\tan x_1 + 2\pi(\theta - sc - x_1) = 0$

If $\alpha = \beta = 0$, $M = K_M\rho R^3$, $N = K_N\rho R^2$, $D = K_D\rho R^3 12(1-\nu^2)/Et^3$, etc.

θ	0°	30°	45°	60°	90°	120°	135°	150°
K_{MA}	0.2500	0.2290	0.1935	0.1466	0.0567	0.0104	0.0027	0.00039
K_{NA}	0.7500	0.6242	0.4944	0.3534	0.1250	0.0216	0.0056	0.00079
K_{MC}	0.7500	0.7216	0.6619	0.5649	0.3067	0.0921	0.0344	0.00778
K_{DH}	0.2146	0.2027	0.1787	0.1422	0.0597	0.0115	0.0031	0.00044
K_{DV}	−0.2337	−0.2209	−0.1955	−0.1573	−0.0700	−0.0150	−0.0043	−0.00066
$K_{\Delta L}$	−0.1399	−0.1333	−0.1198	−0.0986	−0.0465	−0.0106	−0.0031	−0.00050

HYDRAULIC ANALYSIS

AND

CALCULATIONS

Summary of Hydraulic Review

The hydraulic impacts from the use of Cast-In-Place Concrete Pipe (CIPCP) for the proposed storm drain has been reviewed. The hydraulic analysis for the cast in place pipe was performed utilizing the flow rates provided by Stantech Consulting in their StormCAD design files dated 3/9/98. The hydraulic analysis for the preliminary design was based upon a Manning's N of 0.015 as was used in the StormCAD analysis. The invert elevations from the original design were held and the hydraulic control at the outlet was set as the pipe soffit.

A hydraulic analysis was performed utilizing the preliminary Stantech design and several alternate design modifications. The hydraulic analysis was performed using the "Water Surface Pressure Gradient" computer program developed by the Los Angeles County Department of Public Works. See the enclosed reference material for basic computational procedures and criteria.

In order to model the system one-half of the total flow rate was assumed in each barrel of a double barrel pipe system. The final design should include flow equalizing windows constructed at regular intervals to equalize flow and hydraulic gradients in both barrels of the pipe. This is particularly important, immediately upstream and downstream of the proposed junctions where significant flow enters the mainline from lateral storm drains. The preliminary plans do not indicate the details of the junctions and transitions in the system where lateral flows will enter or where the conduit will change configuration. At this time junction losses have been assumed to occur instantaneously in pipe sections at the junction stations shown. The preliminary hydraulic analysis will have to be reviewed after more detail has been determined, regarding these junction and transition structures. A critical issue at the major junctions and transitions is the need to maintain the velocities through the structure, thereby reducing expansion, contraction, and transition losses and also reducing the junction losses calculated using the Pressure + Momentum method of analysis.

The results of the various hydraulic analysis indicates that the pipe sizes shown on the preliminary design drawings produce acceptable results (Pimal Analysis). Principally the flow in the pipes are open channel, supercritical flow except at the outlet. The initial reaches of the pipe will flow under pressure and

create backwater upstream in the system to approximately 32+50, where a hydraulic jump will occur. Unless a larger pipe/box is proposed this condition can not be avoided. There may be a slight problem at the inlet to the lateral line at station 22+00. The hydraulic gradient in the mainline at that junction will be 1619.7 and it appears that the flow line of the natural watercourse being intercepted is approximately 1620. This inlet should be reviewed for its ability to intercept the flows. There may not be a problem since the inflow is relatively small compared to the size of the lateral pipe. If needed, is it possible to extend the inlet upstream to a higher elevation.

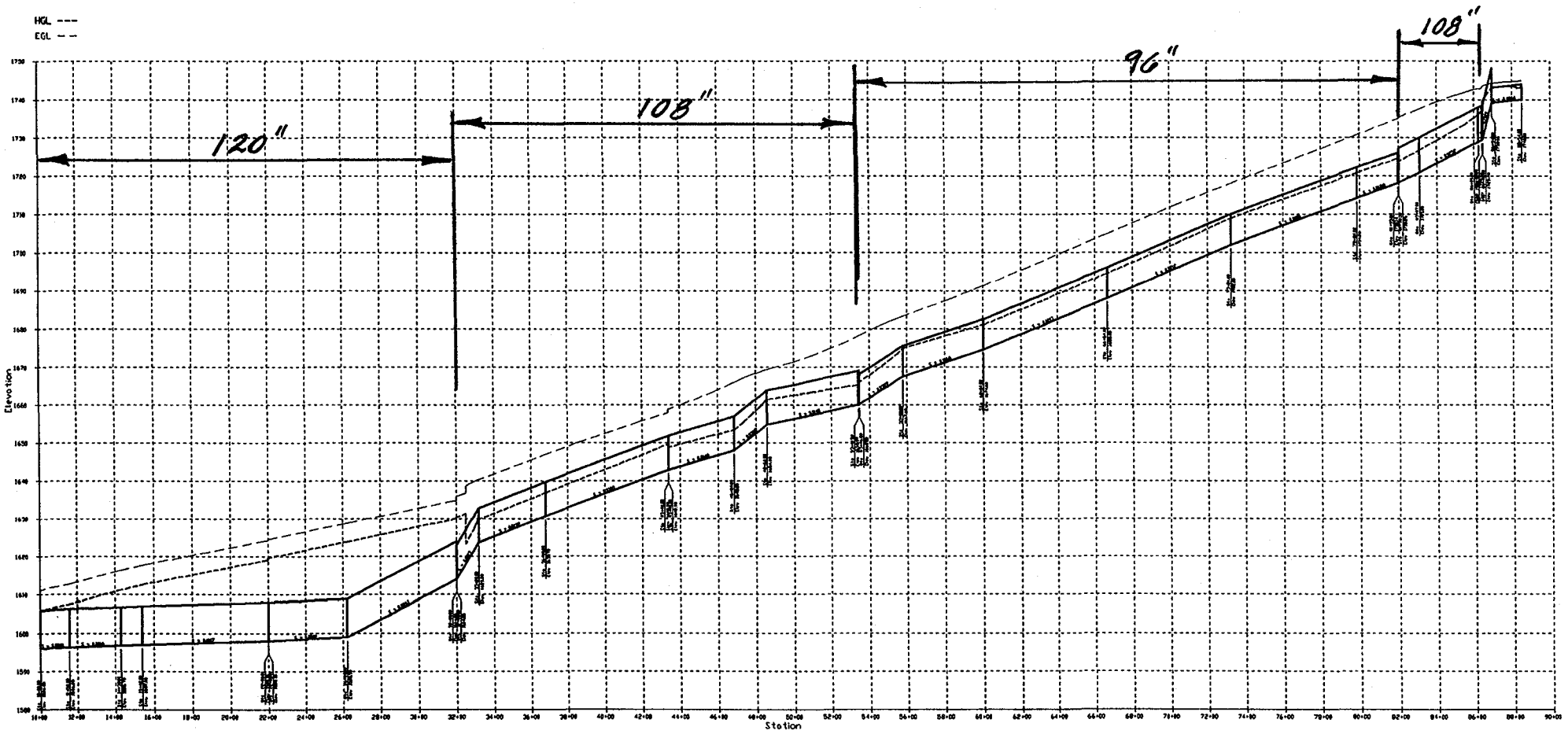
It should be noted that with CIPCP, a 114-inch diameter pipe is not an available size. For this reason a revised design was analyzed using a 108-inch diameter pipe replacing the originally specified 114-inch pipe. The hydraulic analysis for this revision (Pima2 Analysis) indicates that this change will have no significant adverse effects to the operation of the system. The use of the 108-inch diameter pipe will actually help the junction condition at station 32+00. The smaller diameter pipe on the upstream side of the junction increases the upstream momentum. This will in turn decrease the hydraulic losses in the junction and produce a hydraulic gradient at the junction approximately 1.0 foot lower than that with the 114-inch diameter pipe.

A third alternate was reviewed where the system between stations 53+44 and 81+96 has been reduced from the original 108-inch diameter pipe to 96-inch diameter pipe (Pima3 Analysis). With this alternate the flow in this reach of the system will remain supercritical, open channel flow. The most critical section with this change is the reach between 55+80 and 60+04. In this reach the normal depth of flow would be subcritical, pressure flow and a hydraulic jump would be expected upstream, but there is sufficient energy upstream to wash out the potential jump. It should be noted that with the use of a lower Manning's value, the normal depth of flow in this reach may remain supercritical, open channel flow. If this reach could be steepened to approximately 2 percent, or as much as possible, this potential could be eliminated or at least reduced.

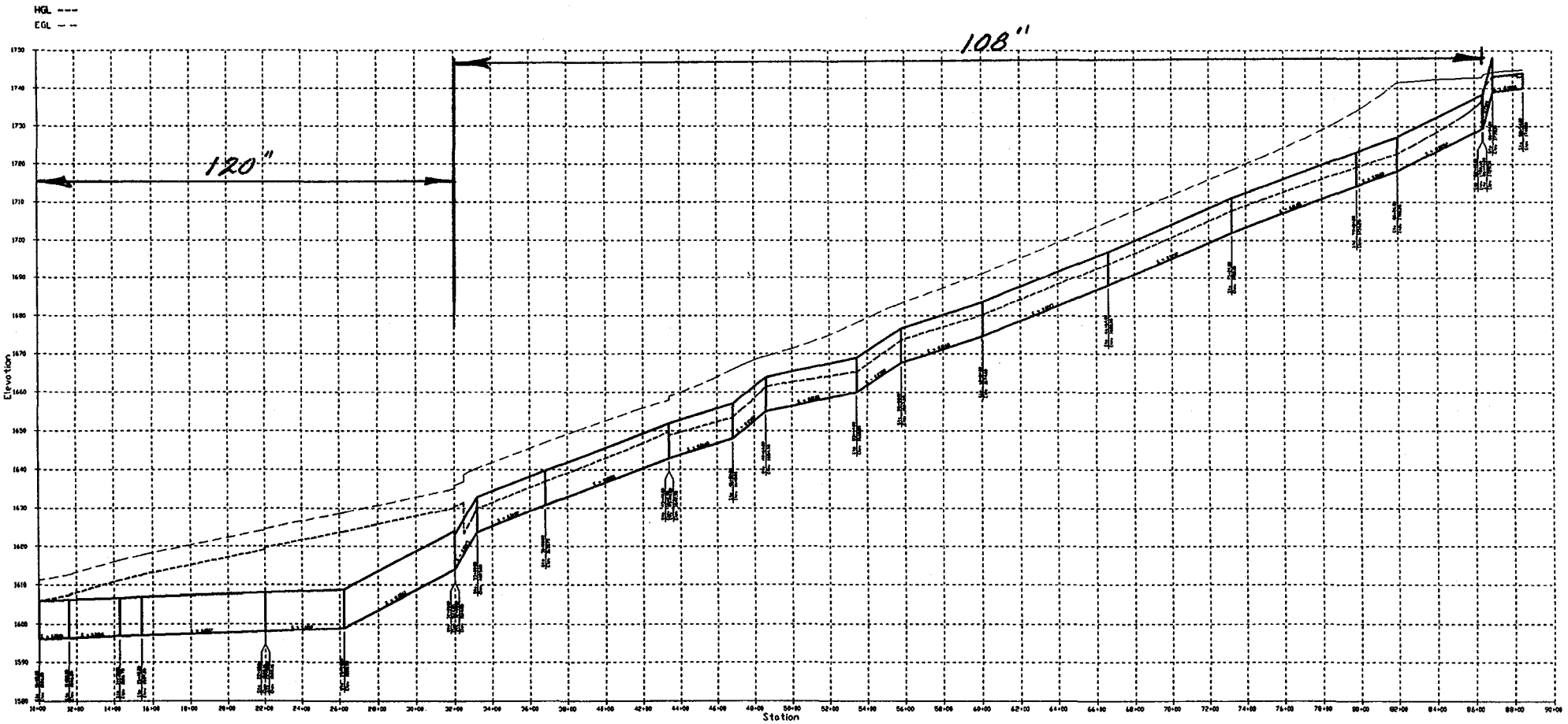
A fourth analysis (Pima4) was prepared using a more detailed analysis of the major junction at station 32+00 and the upstream transition to the existing box culverts. This analysis includes expansion and contraction losses to represent the assumed rectangular chambers created at the junction. With this analysis the

pressure + momentum at the junction changes causing the hydraulic gradient at the junction itself, to be approximately 1.6 feet higher than the previously assumed instantaneously junction. This analysis more accurately models the junction assuming the double barrel pipes are transitioned to rectangular chambers at the junction. It is unclear how the junction at the upstream end of the project near the transition to the existing multi-barreled box culverts will be configured. When this is determined the hydraulic's in this area can be reviewed. Presently we have assumed there would be separate, triple barreled boxes, transitioned to a 108-inch diameter pipe and then a junction downstream.

It is unclear how the lateral storm drain, Line P-16, operates. The proposed hydraulic gradient at the junction with the mainline will be the hydraulic control for this lateral. With all of the various analysis described above, the hydraulic gradient at the junction will be between 1630.4 to 1632.0. With this downstream control, this lateral will be flowing under pressure to the inlet. With the proposed double 66-inch pipes the friction slope in the pipe will be approximately 0.005. The hydraulic gradient, in the pipe, at the entrance may be as high as 1634.0, based upon the junction control from the Pima4 analysis. The inlet should be reviewed to determine its ability to accept the anticipated flows. The ground or rim elevation near the inlet is shown as 1638.5, but it is unclear how the flows enter the system at this point.



PIMA 3



PIMA 2

ORM DRAIN ANALYSIS PLUS

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Version 1.20
erial Number 07010175

Mar 22, 1998 10:25:56

put file : PIMA1.DAT
tput file: PIMA1.OUT

INPUT FILE LISTING

```
   PIMA ROAD COLLECTOR CHANNEL  -  DOUBLE BARREL PIPE,  w/ ½ Q IN EACH PIPE
   100-YEAR FREQUENCY,  w/ OUTLET CONDITION = HGL @ SOFFIT,   ORIGINAL DESIGN
T3 PREPARED BY:     TERRAIN ENGINEERING                  (PIMA1)    3/21/98
CO   1000.001596.00120      015                1606.00
     1158.001596.29120      015
R    1430.001596.79120      015                                  76.0
R    1540.001597.00120      015                                                1
     2200.001598.10120      015
     2200.001598.10120 54   015     39.5       1500.85           30.0
R    2620.001598.90120      015                                                1
R    3200.001614.05120      015                                  40.0
     3200.001614.05114 66   015    203.00      1616.30           30.0
     3320.001623.80114      015                                  40.0
R    3680.001630.70114      015                                                1
R    4340.001642.90114      015
     4340.001642.90108 60   015     63.0       1645.15           30.0
     4684.001648.00108      015                                                1
R    4860.001654.90108      015
R    5344.001660.00108      015                                                1
     5580.001667.60108      015
R    6004.001674.60108      015                                                1
R    6664.001688.00108      015                                                1
     7324.001702.00108      015                                                1
     7984.001714.20108      015                                                1
R    8196.001718.20108      015
R    8640.001729.40108      005
     8644.001729.50108 66   015    109.0       1631.25           30.00
     8694.001739.10  1      015
R    8854.001740.00  1      015
SH                   1      015
```

WATER SURFACE PROFILE - CHANNEL DEFINITION LISTING

ARD CODE	SECT NO	CHN TYPE	NO OF PIERS	AVE PIER WIDTH	HEIGHT 1 DIAMETER	BASE WIDTH	ZL	ZR	INV DROP	Y(1)	Y(2)	Y(3)	Y(4)	Y(5)	Y(6)	Y(7)	Y(8)	Y(9)	Y(10)
CD	1	3	2	.75	4.00	31.50	.00	.00	.00										
[illegible]	54	4			4.50														
[illegible]	60	4			5.00														
CD	66	4			5.50														
[illegible]	108	4			9.00														
[illegible]	114	4			9.50														
CD	120	4			10.00														

WATER SURFACE PROFILE - ELEMENT CARD LISTING

```
ELEMENT NO   1 IS A SYSTEM OUTLET      *         *     *
                U/S DATA   STATION    INVERT  SECT                                W S ELEV
                            1000.00 1596.00  120                                  1606.00

ELEMENT NO   2 IS A REACH              *         *     *
                U/S DATA   STATION    INVERT  SECT              N                          RADIUS  ANGLE  ANG PT  MAN H
                            1158.00 1596.29  120              .015                            .00    .00     .00     0

ELEMENT NO   3 IS A REACH              *         *     *
                U/S DATA   STATION    INVERT  SECT              N                          RADIUS  ANGLE  ANG PT  MAN H
                            1430.00 1596.79  120              .015                            .00  76.00     .00     0

ELEMENT NO   4 IS A REACH              *         *     *
                U/S DATA   STATION    INVERT  SECT              N                          RADIUS  ANGLE  ANG PT  MAN H
                            1540.00 1597.00  120              .015                            .00    .00     .00     1

ELEMENT NO   5 IS A REACH              *         *     *
                U/S DATA   STATION    INVERT  SECT              N                          RADIUS  ANGLE  ANG PT  MAN H
                            2200.00 1598.10  120              .015                            .00    .00     .00     0

ELEMENT NO   6 IS A JUNCTION           *         *     *     *                 *                 *              *
                U/S DATA   STATION    INVERT  SECT LAT-1 LAT-2   N      Q3       Q4    INVERT-3 INVERT-4  PHI 3   PHI 4
                            2200.00 1598.10  120    54     0   .015    39.5       .0  1500.85      .00  30.00     .00
THE ABOVE ELEMENT CONTAINED AN INVERT ELEV WHICH WAS NOT GREATER THAN THE PREVIOUS INVERT ELEV -WARNING
THE ABOVE ELEMENT CONTAINED AN INVERT ELEV WHICH WAS NOT GREATER THAN THE PREVIOUS INVERT ELEV -WARNING

ELEMENT NO   7 IS A REACH              *         *     *
                U/S DATA   STATION    INVERT  SECT              N                          RADIUS  ANGLE  ANG PT  MAN H
                            2620.00 1598.90  120              .015                            .00    .00     .00     1

ELEMENT NO   8 IS A REACH              *         *     *
                U/S DATA   STATION    INVERT  SECT              N                          RADIUS  ANGLE  ANG PT  MAN H
                            3200.00 1614.05  120              .015                            .00  40.00     .00     0

ELEMENT NO   9 IS A JUNCTION           *         *     *     *                 *                 *              *
                U/S DATA   STATION    INVERT  SECT LAT-1 LAT-2   N      Q3       Q4    INVERT-3 INVERT-4  PHI 3   PHI 4
                            3200.00 1614.05  114    66     0   .015   203.0       .0  1616.30      .00  30.00     .00
THE ABOVE ELEMENT CONTAINED AN INVERT ELEV WHICH WAS NOT GREATER THAN THE PREVIOUS INVERT ELEV -WARNING
THE ABOVE ELEMENT CONTAINED AN INVERT ELEV WHICH WAS NOT GREATER THAN THE PREVIOUS INVERT ELEV -WARNING

ELEMENT NO  10 IS A REACH              *         *     *
                U/S DATA   STATION    INVERT  SECT              N                          RADIUS  ANGLE  ANG PT  MAN H
                            3320.00 1623.80  114              .015                            .00  40.00     .00     0
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WATER SURFACE PROFILE - ELEMENT CARD LISTING

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ELEMENT NO  11 IS A REACH          *        *    *
               U/S DATA   STATION    INVERT  SECT              N                          RADIUS  ANGLE  ANG PT  MAN H
                          3680.00 1630.70  114              .015                             .00    .00     .00      1

ELEMENT NO  12 IS A REACH          *        *    *
               U/S DATA   STATION    INVERT  SECT              N                          RADIUS  ANGLE  ANG PT  MAN H
                          4340.00 1642.90  114              .015                             .00    .00     .00      0

ELEMENT NO  13 IS A JUNCTION       *        *    *    *                *                  *              *
               U/S DATA   STATION    INVERT  SECT LAT-1 LAT-2   N      Q3       Q4    INVERT-3 INVERT-4  PHI 3   PHI 4
                          4340.00 1642.90  108    60     0   .015    63.0       .0  1645.15      .00  30.00     .00
THE ABOVE ELEMENT CONTAINED AN INVERT ELEV WHICH WAS NOT GREATER THAN THE PREVIOUS INVERT ELEV -WARNING
THE ABOVE ELEMENT CONTAINED AN INVERT ELEV WHICH WAS NOT GREATER THAN THE PREVIOUS INVERT ELEV -WARNING

ELEMENT NO  14 IS A REACH          *        *    *
               U/S DATA   STATION    INVERT  SECT              N                          RADIUS  ANGLE  ANG PT  MAN H
                          4684.00 1648.00  108              .015                             .00    .00     .00      1

ELEMENT NO  15 IS A REACH          *        *    *
               U/S DATA   STATION    INVERT  SECT              N                          RADIUS  ANGLE  ANG PT  MAN H
                          4860.00 1654.90  108              .015                             .00    .00     .00      0

ELEMENT NO  16 IS A REACH          *        *    *
               U/S DATA   STATION    INVERT  SECT              N                          RADIUS  ANGLE  ANG PT  MAN H
                          5344.00 1660.00  108              .015                             .00    .00     .00      1

ELEMENT NO  17 IS A REACH          *        *    *
               U/S DATA   STATION    INVERT  SECT              N                          RADIUS  ANGLE  ANG PT  MAN H
                          5580.00 1667.60  108              .015                             .00    .00     .00      0

ELEMENT NO  18 IS A REACH          *        *    *
               U/S DATA   STATION    INVERT  SECT              N                          RADIUS  ANGLE  ANG PT  MAN H
                          6004.00 1674.60  108              .015                             .00    .00     .00      1

ELEMENT NO  19 IS A REACH          *        *    *
               U/S DATA   STATION    INVERT  SECT              N                          RADIUS  ANGLE  ANG PT  MAN H
                          6664.00 1688.00  108              .015                             .00    .00     .00      1

ELEMENT NO  20 IS A REACH          *        *    *
               U/S DATA   STATION    INVERT  SECT              N                          RADIUS  ANGLE  ANG PT  MAN H
                          7324.00 1702.00  108              .015                             .00    .00     .00      1

ELEMENT NO  21 IS A REACH          *        *    *
               U/S DATA   STATION    INVERT  SECT              N                          RADIUS  ANGLE  ANG PT  MAN H
                          7984.00 1714.20  108              .015                             .00    .00     .00      1

ELEMENT NO  22 IS A REACH          *        *    *
               U/S DATA   STATION    INVERT  SECT              N                          RADIUS  ANGLE  ANG PT  MAN H
                          8196.00 1718.20  108              .015                             .00    .00     .00      0
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WATER SURFACE PROFILE - ELEMENT CARD LISTING

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ELEMENT NO  23 IS A REACH            *        *    *
                U/S DATA   STATION    INVERT  SECT              N                                RADIUS  ANGLE  ANG PT  MAN H
                            8640.00 1729.40  108              .005                                   .00    .00     .00      0

ELEMENT NO  24 IS A JUNCTION         *        *    *    *                *                 *              *
                U/S DATA   STATION    INVERT  SECT LAT-1 LAT-2   N      Q3       Q4    INVERT-3 INVERT-4  PHI 3   PHI 4
                            8644.00 1729.50  108    66     0   .015    109.0       .0  1631.25      .00  30.00     .00

ELEMENT NO  25 IS A TRANSITION       *        *    *
                U/S DATA   STATION    INVERT  SECT              N
                            8694.00 1739.10    1              .015

ELEMENT NO  26 IS A REACH            *        *    *
                U/S DATA   STATION    INVERT  SECT              N                                RADIUS  ANGLE  ANG PT  MAN H
                            8854.00 1740.00    1              .015                                   .00    .00     .00      0

ELEMENT NO  27 IS A SYSTEM HEADWORKS                 *                     *
                U/S DATA   STATION    INVERT  SECT                                   W S ELEV
                            8854.00 1740.00    1                                        .00
NO EDIT ERRORS ENCOUNTERED-COMPUTATION IS NOW BEGINNING

** WARNING NO. 2 ** - WATER SURFACE ELEVATION GIVEN IS LESS THAN OR EQUALS INVERT ELEVATION IN HDWKDS, W.S.ELEV = INV + DC
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WATER SURFACE PROFILE LISTING

PIMA ROAD COLLECTOR CHANNEL - DOUBLE BARREL PIPE, w/ ½ Q IN EACH PIPE
100-YEAR FREQUENCY, w/ OUTLET CONDITION = HGL @ SOFFIT, ORIGINAL DESIGN
PREPARED BY: TERRAIN ENGINEERING (PIMA1) 3/21/98

STATION	INVERT ELEV	DEPTH OF FLOW	W.S. ELEV	Q	VEL	VEL HEAD	ENERGY GRD.EL.	SUPER ELEV	CRITICAL DEPTH		HGT/ DIA	BASE/ ID NO.	ZL	NO PIER	AVBPR
L/ELEM	SO					SF AVE	HF			NORM DEPTH			ZR		
1000.00	1596.00	10.00	1606.00	1431.0	18.22	5.16	1611.16	.00	8.88		10.00	.00	.00	0	.00
158.00	.00184					.00997	1.58			10.00			.00		
1158.00	1596.29	11.29	1607.58	1431.0	18.22	5.16	1612.73	.00	8.88		10.00	.00	.00	0	.00
272.00	.00184					.00997	2.71			10.00			.00		
1430.00	1596.79	14.44	1611.23	1431.0	18.22	5.16	1616.39	.00	8.88		10.00	.00	.00	0	.00
110.00	.00191					.00997	1.10			10.00			.00		
1540.00	1597.00	15.59	1612.59	1431.0	18.22	5.16	1617.75	.00	8.88		10.00	.00	.00	0	.00
660.00	.00167					.00997	6.58			10.00			.00		
2200.00	1598.10	21.07	1619.17	1431.0	18.22	5.16	1624.33	.00	8.88		10.00	.00	.00	0	.00
JUNCT STR	.00000					.00970	.00						.00		
2200.00	1598.10	21.60	1619.70	1391.5	17.72	4.88	1624.58	.00	8.80		10.00	.00	.00	0	.00
420.00	.00190					.00943	3.96			10.00			.00		
2620.00	1598.90	25.00	1623.90	1391.5	17.72	4.88	1628.78	.00	8.80		10.00	.00	.00	0	.00
580.00	.02612					.00943	5.47			5.59			.00		
3200.00	1614.05	15.97	1630.02	1391.5	17.72	4.88	1634.90	.00	8.80		10.00	.00	.00	0	.00
JUNCT STR	.00000					.00923	.00						.00		
3200.00	1614.05	17.31	1631.36	1188.5	16.77	4.37	1635.73	.00	8.26		9.50	.00	.00	0	.00
60.44	.08125					.00904	.55			3.78			.00		
3260.44	1618.96	13.24	1632.20	1188.5	16.77	4.37	1636.57	.00	8.26		9.50	.00	.00	0	.00
HYDRAULIC JUMP													.00		
3260.44	1618.96	5.08	1624.04	1188.5	30.80	14.75	1638.79	.00	8.26		9.50	.00	.00	0	.00
10.26	.08125					.02807	.29			3.78			.00		

WATER SURFACE PROFILE LISTING

PIMA ROAD COLLECTOR CHANNEL - DOUBLE BARREL PIPE, w/ ½ Q IN EACH PIPE
100-YEAR FREQUENCY, w/ OUTLET CONDITION = HGL @ SOFFIT, ORIGINAL DESIGN
PREPARED BY: TERRAIN ENGINEERING (PIMA1) 3/21/98

STATION	INVERT ELEV	DEPTH OF FLOW	W.S. ELEV	Q	VEL	VEL HEAD	ENERGY GRD.EL.	SUPER ELEV	CRITICAL DEPTH		HGT/ DIA	BASE/ ID NO.	ZL	NO PIER	AVBPR
L/ELEM	SO					SF AVE	HF			NORM DEPTH			ZR		
3270.70	1619.79	5.17	1624.96	1188.5	30.14	14.12	1639.09	.00	8.26		9.50	.00	.00	0	.00
19.43	.08125					.02567	.50			3.78			.00		
3290.13	1621.37	5.37	1626.75	1188.5	28.74	12.84	1639.58	.00	8.26		9.50	.00	.00	0	.00
16.25	.08125					.02268	.37			3.78			.00		
3306.38	1622.69	5.59	1628.28	1188.5	27.40	11.67	1639.95	.00	8.26		9.50	.00	.00	0	.00
13.62	.08125					.02006	.27			3.78			.00		
3320.00	1623.80	5.82	1629.62	1188.5	26.13	10.61	1640.23	.00	8.26		9.50	.00	.00	0	.00
360.00	.01917					.01846	6.65			5.78			.00		
3680.00	1630.70	5.90	1636.60	1188.5	25.71	10.28	1646.87	.00	8.26		9.50	.00	.00	0	.00
.00	.01917					.01809	.00			5.78			.00		
3680.00	1630.70	5.90	1636.60	1188.5	25.71	10.28	1646.87	.00	8.26		9.50	.00	.00	0	.00
457.76	.01849					.01725	7.90			5.85			.00		
4137.75	1639.16	6.09	1645.26	1188.5	24.74	9.51	1654.77	.00	8.26		9.50	.00	.00	0	.00
202.25	.01849					.01549	3.13			5.85			.00		
4340.00	1642.90	6.35	1649.25	1188.5	23.59	8.65	1657.90	.00	8.26		9.50	.00	.00	0	.00
JUNCT STR	.00000					.01636	.00						.00		
4340.00	1642.90	5.94	1648.84	1125.5	25.29	9.94	1658.77	.00	8.06		9.00	.00	.00	0	.00
JUNCT STR	.00000					.01814	.00						.00		
4340.00	1642.90	5.94	1648.84	1125.5	25.29	9.94	1658.77	.00	8.06		9.00	.00	.00	0	.00
85.60	.01483					.01864	1.60			6.40			.00		
4425.60	1644.17	5.82	1649.99	1125.5	25.84	10.38	1660.37	.00	8.06		9.00	.00	.00	0	.00
145.23	.01483					.02036	2.96			6.40			.00		

WATER SURFACE PROFILE LISTING

PIMA ROAD COLLECTOR CHANNEL - DOUBLE BARREL PIPE, w/ ½ Q IN EACH PIPE
100-YEAR FREQUENCY, w/ OUTLET CONDITION = HGL @ SOFFIT, ORIGINAL DESIGN
PREPARED BY: TERRAIN ENGINEERING (PIMA1) 3/21/98

STATION	INVERT ELEV	DEPTH OF FLOW	W.S. ELEV	Q	VEL	VEL HEAD	ENERGY GRD.EL.	SUPER ELEV	CRITICAL DEPTH		HGT/ DIA	BASE/ ID NO.	ZL	NO PIER	AVBPR
L/ELEM	SO					SF AVE	HF			NORM DEPTH			ZR		
4570.83	1646.32	5.59	1651.91	1125.5	27.10	11.42	1663.33	.00	8.06		9.00	.00	.00	0	.00
113.17	.01483					.02297	2.60			6.40			.00		
4684.00	1648.00	5.37	1653.37	1125.5	28.43	12.56	1665.93	.00	8.06		9.00	.00	.00	0	.00
.00	.01483					.02437	.00			6.40			.00		
4684.00	1648.00	5.37	1653.37	1125.5	28.43	12.56	1665.93	.00	8.06		9.00	.00	.00	0	.00
52.21	.03920					.02310	1.21			4.63			.00		
4736.21	1650.05	5.57	1655.62	1125.5	27.23	11.52	1667.13	.00	8.06		9.00	.00	.00	0	.00
43.80	.03920					.02059	.90			4.63			.00		
4780.01	1651.76	5.80	1657.57	1125.5	25.96	10.47	1668.04	.00	8.06		9.00	.00	.00	0	.00
33.65	.03920					.01828	.62			4.63			.00		
4813.66	1653.08	6.05	1659.13	1125.5	24.75	9.52	1668.65	.00	8.06		9.00	.00	.00	0	.00
26.13	.03920					.01627	.43			4.63			.00		
4839.79	1654.11	6.32	1660.42	1125.5	23.60	8.65	1669.08	.00	8.06		9.00	.00	.00	0	.00
20.21	.03920					.01452	.29			4.63			.00		
4860.00	1654.90	6.60	1661.50	1125.5	22.50	7.87	1669.37	.00	8.06		9.00	.00	.00	0	.00
17.33	.01054					.01380	.24			7.49			.00		
4877.33	1655.08	6.57	1661.65	1125.5	22.64	7.96	1669.61	.00	8.06		9.00	.00	.00	0	.00
122.02	.01054					.01473	1.80			7.49			.00		
4999.35	1656.37	6.28	1662.65	1125.5	23.74	8.76	1671.41	.00	8.06		9.00	.00	.00	0	.00
102.63	.01054					.01651	1.69			7.49			.00		
5101.99	1657.45	6.02	1663.47	1125.5	24.90	9.64	1673.10	.00	8.06		9.00	.00	.00	0	.00
89.44	.01054					.01856	1.66			7.49			.00		

WATER SURFACE PROFILE LISTING

PIMA ROAD COLLECTOR CHANNEL - DOUBLE BARREL PIPE, w/ ½ Q IN EACH PIPE
100-YEAR FREQUENCY, w/ OUTLET CONDITION = HGL @ SOFFIT, ORIGINAL DESIGN
PREPARED BY: TERRAIN ENGINEERING (PIMA1) 3/21/98

STATION	INVERT ELEV	DEPTH OF FLOW	W.S. ELEV	Q	VEL	VEL HEAD	ENERGY GRD.EL.	SUPER ELEV	CRITICAL DEPTH		HGT/ DIA	BASE/ ID NO.	ZL	NO PIER	AVBPR
L/ELEM	SO					SF AVE	HF			NORM DEPTH			ZR		
5191.43	1658.39	5.77	1664.16	1125.5	26.12	10.60	1674.76	.00	8.06		9.00	.00	.00	0	.00
79.91	.01054					.02091	1.67			7.49			.00		
5271.34	1659.23	5.54	1664.77	1125.5	27.39	11.66	1676.43	.00	8.06		9.00	.00	.00	0	.00
72.66	.01054					.02360	1.71			7.49			.00		
5344.00	1660.00	5.32	1665.32	1125.5	28.73	12.82	1678.15	.00	8.06		9.00	.00	.00	0	.00
109.54	.03220					.02362	2.59			4.92			.00		
5453.54	1663.53	5.54	1669.07	1125.5	27.40	11.67	1680.74	.00	8.06		9.00	.00	.00	0	.00
73.75	.03220					.02094	1.54			4.92			.00		
5527.29	1665.90	5.77	1671.67	1125.5	26.13	10.61	1682.28	.00	8.06		9.00	.00	.00	0	.00
52.71	.03220					.01858	.98			4.92			.00		
5580.00	1667.60	6.01	1673.61	1125.5	24.91	9.64	1683.26	.00	8.06		9.00	.00	.00	0	.00
142.95	.01651					.01776	2.54			6.14			.00		
5722.95	1669.96	5.95	1675.91	1125.5	25.23	9.89	1685.80	.00	8.06		9.00	.00	.00	0	.00
281.05	.01651					.01917	5.39			6.14			.00		
6004.00	1674.60	5.71	1680.31	1125.5	26.46	10.88	1691.19	.00	8.06		9.00	.00	.00	0	.00
6.50	.02030					.02031	.13			5.71			.00		
6010.50	1674.73	5.71	1680.44	1125.5	26.46	10.88	1691.32	.00	8.06		9.00	.00	.00	0	.00
653.50	.02030					.02076	13.57			5.71			.00		
6664.00	1688.00	5.62	1693.62	1125.5	26.92	11.26	1704.88	.00	8.06		9.00	.00	.00	0	.00
660.00	.02121					.02061	13.60			5.62			.00		
7324.00	1702.00	5.74	1707.74	1125.5	26.30	10.75	1718.49	.00	8.06		9.00	.00	.00	0	.00
.00	.02121					.02001	.00			5.62			.00		

WATER SURFACE PROFILE LISTING

PIMA ROAD COLLECTOR CHANNEL - DOUBLE BARREL PIPE, w/ ½ Q IN EACH PIPE
100-YEAR FREQUENCY, w/ OUTLET CONDITION = HGL @ SOFFIT, ORIGINAL DESIGN
PREPARED BY: TERRAIN ENGINEERING (PIMA1) 3/21/98

STATION	INVERT ELEV	DEPTH OF FLOW	W.S. ELEV	Q	VEL	VEL HEAD	ENERGY GRD.EL.	SUPER ELEV	CRITICAL DEPTH		HGT/ DIA	BASE/ ID NO.	ZL	NO PIER	AVBPR
L/ELEM	SO					SF AVE	HF			NORM DEPTH			ZR		
7324.00	1702.00	5.74	1707.74	1125.5	26.30	10.75	1718.49	.00	8.06		9.00	.00	.00	0	.00
168.67	.01849					.02053	3.46			5.90			.00		
7492.67	1705.12	5.64	1710.75	1125.5	26.84	11.20	1721.95	.00	8.06		9.00	.00	.00	0	.00
228.19	.01849					.02241	5.11			5.90			.00		
7720.86	1709.34	5.41	1714.75	1125.5	28.15	12.32	1727.07	.00	8.06		9.00	.00	.00	0	.00
149.41	.01849					.02532	3.78			5.90			.00		
7870.27	1712.10	5.20	1717.30	1125.5	29.53	13.55	1730.85	.00	8.06		9.00	.00	.00	0	.00
113.73	.01849					.02865	3.26			5.90			.00		
7984.00	1714.20	5.01	1719.21	1125.5	30.97	14.90	1734.11	.00	8.06		9.00	.00	.00	0	.00
47.18	.01887					.03133	1.48			5.85			.00		
8031.18	1715.09	4.92	1720.01	1125.5	31.66	15.58	1735.59	.00	8.06		9.00	.00	.00	0	.00
88.46	.01887					.03440	3.04			5.85			.00		
8119.64	1716.76	4.73	1721.49	1125.5	33.21	17.14	1738.63	.00	8.06		9.00	.00	.00	0	.00
76.36	.01887					.03902	2.98			5.85			.00		
8196.00	1718.20	4.56	1722.76	1125.5	34.83	18.85	1741.61	.00	8.06		9.00	.00	.00	0	.00
-.00	.01887					.02305	.00			5.85			.00		
8196.00	1718.20	4.56	1722.76	1125.5	34.83	18.85	1741.61	.00	8.06		9.00	.00	.00	0	.00
.89	.02523					.00461	.00			2.86			.00		
8196.89	1718.22	4.56	1722.78	1125.5	34.81	18.83	1741.61	.00	8.06		9.00	.00	.00	0	.00
73.56	.02523					.00433	.32			2.86			.00		
8270.46	1720.08	4.73	1724.81	1125.5	33.19	17.12	1741.93	.00	8.06		9.00	.00	.00	0	.00
64.11	.02523					.00382	.24			2.86			.00		

WATER SURFACE PROFILE LISTING

PIMA ROAD COLLECTOR CHANNEL - DOUBLE BARREL PIPE, w/ ½ Q IN EACH PIPE
100-YEAR FREQUENCY, w/ OUTLET CONDITION = HGL @ SOFFIT, ORIGINAL DESIGN
PREPARED BY: TERRAIN ENGINEERING (PIMA1) 3/21/98

STATION	INVERT ELEV	DEPTH OF FLOW	W.S. ELEV	Q	VEL	VEL HEAD	ENERGY GRD.EL.	SUPER ELEV	CRITICAL DEPTH		HGT/ DIA	BASE/ ID NO.	ZL	NO PIER	AVBPR
L/ELEM	SO					SF AVE	HF			NORM DEPTH			ZR		
8334.57	1721.70	4.92	1726.61	1125.5	31.65	15.56	1742.18	.00	8.06		9.00	.00	.00	0	.00
55.82	.02523					.00337	.19			2.86			.00		
8390.38	1723.10	5.11	1728.22	1125.5	30.17	14.15	1742.36	.00	8.06		9.00	.00	.00	0	.00
48.65	.02523					.00298	.14			2.86			.00		
8439.03	1724.33	5.32	1729.65	1125.5	28.77	12.86	1742.51	.00	8.06		9.00	.00	.00	0	.00
42.15	.02523					.00263	.11			2.86			.00		
8481.18	1725.39	5.53	1730.93	1125.5	27.43	11.69	1742.62	.00	8.06		9.00	.00	.00	0	.00
36.39	.02523					.00233	.08			2.86			.00		
8517.57	1726.31	5.76	1732.07	1125.5	26.15	10.63	1742.71	.00	8.06		9.00	.00	.00	0	.00
31.11	.02523					.00207	.06			2.86			.00		
8548.69	1727.10	6.01	1733.11	1125.5	24.94	9.66	1742.77	.00	8.06		9.00	.00	.00	0	.00
26.33	.02523					.00184	.05			2.86			.00		
8575.01	1727.76	6.27	1734.03	1125.5	23.78	8.79	1742.82	.00	8.06		9.00	.00	.00	0	.00
21.87	.02523					.00164	.04			2.86			.00		
8596.88	1728.31	6.56	1734.87	1125.5	22.67	7.99	1742.85	.00	8.06		9.00	.00	.00	0	.00
17.52	.02523					.00147	.03			2.86			.00		
8614.40	1728.75	6.87	1735.62	1125.5	21.62	7.26	1742.88	.00	8.06		9.00	.00	.00	0	.00
13.31	.02523					.00132	.02			2.86			.00		
8627.71	1729.09	7.21	1736.30	1125.5	20.61	6.60	1742.90	.00	8.06		9.00	.00	.00	0	.00
8.87	.02523					.00120	.01			2.86			.00		
8636.57	1729.31	7.59	1736.91	1125.5	19.65	6.00	1742.91	.00	8.06		9.00	.00	.00	0	.00
3.43	.02523					.00110	.00			2.86			.00		

WATER SURFACE PROFILE LISTING

PIMA ROAD COLLECTOR CHANNEL - DOUBLE BARREL PIPE, w/ ½ Q IN EACH PIPE
100-YEAR FREQUENCY, w/ OUTLET CONDITION = HGL @ SOFFIT, ORIGINAL DESIGN
PREPARED BY: TERRAIN ENGINEERING (PIMA1) 3/21/98

STATION	INVERT ELEV	DEPTH OF FLOW	W.S. ELEV	Q	VEL	VEL HEAD	ENERGY GRD.EL.	SUPER ELEV	CRITICAL DEPTH		HGT/ DIA	BASE/ ID NO.	ZL	NO PIER	AVBPR
L/ELEM	SO					SF AVE	HF			NORM DEPTH			ZR		
8640.00	1729.40	8.06	1737.46	1125.5	18.73	5.45	1742.91	.00	8.06		9.00	.00	.00	0	.00
NCT STR	.02499					.00919	.04						.00		
8644.00	1729.50	10.21	1739.71	1016.5	15.98	3.97	1743.68	.00	7.77		9.00	.00	.00	0	.00
ANS STR	.19200					.00673	.34						.00		
8694.00	1739.10	4.07	1743.17	1016.5	8.52	1.13	1744.30	.00	3.29		4.00	31.50	.00	2	.75
71.14	.00563					.00464	.33			3.00			.00		
8765.14	1739.50	4.00	1743.50	1016.5	8.52	1.13	1744.63	.00	3.29		4.00	31.50	.00	2	.75
25.48	.00563					.00273	.07			3.00			.00		
8790.62	1739.64	3.81	1743.46	1016.5	8.89	1.23	1744.68	.00	3.29		4.00	31.50	.00	2	.75
21.49	.00563					.00308	.07			3.00			.00		
8812.11	1739.76	3.64	1743.40	1016.5	9.32	1.35	1744.75	.00	3.29		4.00	31.50	.00	2	.75
15.06	.00563					.00349	.05			3.00			.00		
8827.17	1739.85	3.48	1743.33	1016.5	9.73	1.47	1744.80	.00	3.29		4.00	31.50	.00	2	.75
HYDRAULIC JUMP													.00		
8827.17	1739.85	3.11	1742.96	1016.5	10.90	1.85	1744.80	.00	3.29		4.00	31.50	.00	2	.75
15.06	.00563					.00502	.08			3.00			.00		
8842.23	1739.93	3.14	1743.07	1016.5	10.80	1.81	1744.88	.00	3.29		4.00	31.50	.00	2	.75
11.77	.00563					.00464	.05			3.00			.00		
8854.00	1740.00	3.29	1743.29	1016.5	10.29	1.65	1744.94	.00	3.29		4.00	31.50	.00	2	.75

STORM DRAIN ANALYSIS PLUS

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rsion 1.20
rial Number 07010175

Mar 22, 1998 10:26:23

put file : PIMA2.DAT
Output file: PIMA2.OUT

INPUT FILE LISTING

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T1 PIMA ROAD COLLECTOR CHANNEL  -  DOUBLE BARREL PIPE,  w/ ½ Q IN EACH PIPE
T2 100-YEAR FREQUENCY,  w/ OUTLET CONDITION = HGL @ SOFFIT,   REVISED DESIGN
T3 PREPARED BY:     TERRAIN ENGINEERING                  (PIMA2)    3/21/98
   1000.001596.00120      015                1606.00
R  1158.001596.29120      015
R  1430.001596.79120      015                                  76.0
   1540.001597.00120      015                                                1
   2200.001598.10120      015
JX 2200.001598.10120 54   015     39.5       1500.85          30.0
R  2620.001598.90120      015                                                1
   3200.001614.05120      015                                  40.0
   3200.001614.05108 66   015    203.00      1616.30          30.0
R  3320.001623.80108      015                                  40.0
R  3680.001630.70108      015                                                1
   4340.001642.90108      015
JX 4340.001642.90108 60   015     63.0       1645.15          30.0
R  4684.001648.00108      015                                                1
   4860.001654.90108      015
   5344.001660.00108      015                                                1
R  5580.001667.60108      015
R  6004.001674.60108      015                                                1
   6664.001688.00108      015                                                1
   7324.001702.00108      015                                                1
R  7984.001714.20108      015                                                1
R  8196.001718.20108      015
   8640.001729.40108      005
   8644.001729.50108 66   015    109.0       1631.25          30.00
TS 8694.001739.10  1      015
R  8854.001740.00  1      015
                   1      015
```

WATER SURFACE PROFILE - CHANNEL DEFINITION LISTING

RD CODE	SECT NO	CHN TYPE	NO OF PIERS	AVE PIER WIDTH	HEIGHT 1 DIAMETER	BASE WIDTH	ZL	ZR	INV DROP	Y(1)	Y(2)	Y(3)	Y(4)	Y(5)	Y(6)	Y(7)	Y(8)	Y(9)	Y(10)
	1	3	2	.75	4.00	31.50	.00	.00	.00										
	54	4			4.50														
CD	60	4			5.00														
CD	66	4			5.50														
	108	4			9.00														
	114	4			9.50														
CD	120	4			10.00														

WATER SURFACE PROFILE - ELEMENT CARD LISTING

```
ELEMENT NO   1 IS A SYSTEM OUTLET      *         *     *
                U/S DATA   STATION    INVERT  SECT                                W S ELEV
                            1000.00 1596.00  120                                  1606.00

ELEMENT NO   2 IS A REACH              *         *     *
                U/S DATA   STATION    INVERT  SECT              N                          RADIUS  ANGLE  ANG PT  MAN H
                            1158.00 1596.29  120              .015                            .00    .00     .00     0

ELEMENT NO   3 IS A REACH              *         *     *
                U/S DATA   STATION    INVERT  SECT              N                          RADIUS  ANGLE  ANG PT  MAN H
                            1430.00 1596.79  120              .015                            .00  76.00     .00     0

ELEMENT NO   4 IS A REACH              *         *     *
                U/S DATA   STATION    INVERT  SECT              N                          RADIUS  ANGLE  ANG PT  MAN H
                            1540.00 1597.00  120              .015                            .00    .00     .00     1

ELEMENT NO   5 IS A REACH              *         *     *
                U/S DATA   STATION    INVERT  SECT              N                          RADIUS  ANGLE  ANG PT  MAN H
                            2200.00 1598.10  120              .015                            .00    .00     .00     0

ELEMENT NO   6 IS A JUNCTION           *         *     *     *                 *                 *              *
                U/S DATA   STATION    INVERT  SECT LAT-1 LAT-2  N      Q3       Q4    INVERT-3 INVERT-4  PHI 3   PHI 4
                            2200.00 1598.10  120    54     0  .015    39.5       .0  1500.85      .00  30.00     .00
THE ABOVE ELEMENT CONTAINED AN INVERT ELEV WHICH WAS NOT GREATER THAN THE PREVIOUS INVERT ELEV -WARNING
THE ABOVE ELEMENT CONTAINED AN INVERT ELEV WHICH WAS NOT GREATER THAN THE PREVIOUS INVERT ELEV -WARNING

ELEMENT NO   7 IS A REACH              *         *     *
                U/S DATA   STATION    INVERT  SECT              N                          RADIUS  ANGLE  ANG PT  MAN H
                            2620.00 1598.90  120              .015                            .00    .00     .00     1

ELEMENT NO   8 IS A REACH              *         *     *
                U/S DATA   STATION    INVERT  SECT              N                          RADIUS  ANGLE  ANG PT  MAN H
                            3200.00 1614.05  120              .015                            .00  40.00     .00     0

ELEMENT NO   9 IS A JUNCTION           *         *     *     *                 *                 *              *
                U/S DATA   STATION    INVERT  SECT LAT-1 LAT-2  N      Q3       Q4    INVERT-3 INVERT-4  PHI 3   PHI 4
                            3200.00 1614.05  108    66     0  .015   203.0       .0  1616.30      .00  30.00     .00
THE ABOVE ELEMENT CONTAINED AN INVERT ELEV WHICH WAS NOT GREATER THAN THE PREVIOUS INVERT ELEV -WARNING
THE ABOVE ELEMENT CONTAINED AN INVERT ELEV WHICH WAS NOT GREATER THAN THE PREVIOUS INVERT ELEV -WARNING

ELEMENT NO  10 IS A REACH              *         *     *
                U/S DATA   STATION    INVERT  SECT              N                          RADIUS  ANGLE  ANG PT  MAN H
                            3320.00 1623.80  108              .015                            .00  40.00     .00     0
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WATER SURFACE PROFILE - ELEMENT CARD LISTING

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ELEMENT NO  11 IS A REACH            *        *     *
                U/S DATA   STATION    INVERT  SECT              N                                RADIUS  ANGLE  ANG PT  MAN H
                            3680.00 1630.70  108              .015                                  .00    .00     .00      1

ELEMENT NO  12 IS A REACH            *        *     *
                U/S DATA   STATION    INVERT  SECT              N                                RADIUS  ANGLE  ANG PT  MAN H
                            4340.00 1642.90  108              .015                                  .00    .00     .00      0

ELEMENT NO  13 IS A JUNCTION         *        *     *     *                 *                 *              *
                U/S DATA   STATION    INVERT  SECT LAT-1 LAT-2   N      Q3       Q4    INVERT-3 INVERT-4  PHI 3   PHI 4
                            4340.00 1642.90  108    60     0   .015     63.0       .0  1645.15      .00  30.00     .00
THE ABOVE ELEMENT CONTAINED AN INVERT ELEV WHICH WAS NOT GREATER THAN THE PREVIOUS INVERT ELEV -WARNING
THE ABOVE ELEMENT CONTAINED AN INVERT ELEV WHICH WAS NOT GREATER THAN THE PREVIOUS INVERT ELEV -WARNING

ELEMENT NO  14 IS A REACH            *        *     *
                U/S DATA   STATION    INVERT  SECT              N                                RADIUS  ANGLE  ANG PT  MAN H
                            4684.00 1648.00  108              .015                                  .00    .00     .00      1

ELEMENT NO  15 IS A REACH            *        *     *
                U/S DATA   STATION    INVERT  SECT              N                                RADIUS  ANGLE  ANG PT  MAN H
                            4860.00 1654.90  108              .015                                  .00    .00     .00      0

ELEMENT NO  16 IS A REACH            *        *     *
                U/S DATA   STATION    INVERT  SECT              N                                RADIUS  ANGLE  ANG PT  MAN H
                            5344.00 1660.00  108              .015                                  .00    .00     .00      1

ELEMENT NO  17 IS A REACH            *        *     *
                U/S DATA   STATION    INVERT  SECT              N                                RADIUS  ANGLE  ANG PT  MAN H
                            5580.00 1667.60  108              .015                                  .00    .00     .00      0

ELEMENT NO  18 IS A REACH            *        *     *
                U/S DATA   STATION    INVERT  SECT              N                                RADIUS  ANGLE  ANG PT  MAN H
                            6004.00 1674.60  108              .015                                  .00    .00     .00      1

ELEMENT NO  19 IS A REACH            *        *     *
                U/S DATA   STATION    INVERT  SECT              N                                RADIUS  ANGLE  ANG PT  MAN H
                            6664.00 1688.00  108              .015                                  .00    .00     .00      1

ELEMENT NO  20 IS A REACH            *        *     *
                U/S DATA   STATION    INVERT  SECT              N                                RADIUS  ANGLE  ANG PT  MAN H
                            7324.00 1702.00  108              .015                                  .00    .00     .00      1

ELEMENT NO  21 IS A REACH            *        *     *
                U/S DATA   STATION    INVERT  SECT              N                                RADIUS  ANGLE  ANG PT  MAN H
                            7984.00 1714.20  108              .015                                  .00    .00     .00      1

ELEMENT NO  22 IS A REACH            *        *     *
                U/S DATA   STATION    INVERT  SECT              N                                RADIUS  ANGLE  ANG PT  MAN H
                            8196.00 1718.20  108              .015                                  .00    .00     .00      0
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WATER SURFACE PROFILE - ELEMENT CARD LISTING

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ELEMENT NO  23 IS A REACH            *        *    *
                U/S DATA   STATION    INVERT  SECT              N                                RADIUS  ANGLE  ANG PT  MAN H
                           8640.00 1729.40  108              .005                                  .00    .00     .00     0

ELEMENT NO  24 IS A JUNCTION         *        *    *    *                *                 *              *
                U/S DATA   STATION    INVERT  SECT LAT-1 LAT-2  N      Q3       Q4    INVERT-3 INVERT-4  PHI 3   PHI 4
                           8644.00 1729.50  108    66     0  .015    109.0       .0  1631.25      .00  30.00     .00

ELEMENT NO  25 IS A TRANSITION       *        *    *
                U/S DATA   STATION    INVERT  SECT              N
                           8694.00 1739.10    1              .015

ELEMENT NO  26 IS A REACH            *        *    *
                U/S DATA   STATION    INVERT  SECT              N                                RADIUS  ANGLE  ANG PT  MAN H
                           8854.00 1740.00    1              .015                                  .00    .00     .00     0

ELEMENT NO  27 IS A SYSTEM HEADWORKS                 *                     *
                U/S DATA   STATION    INVERT  SECT                                     W S ELEV
                           8854.00 1740.00    1                                          .00
NO EDIT ERRORS ENCOUNTERED-COMPUTATION IS NOW BEGINNING

WARNING NO. 2 ** - WATER SURFACE ELEVATION GIVEN IS LESS THAN OR EQUALS INVERT ELEVATION IN HDWKDS, W.S.ELEV = INV + DC
```

WATER SURFACE PROFILE LISTING

PIMA ROAD COLLECTOR CHANNEL - DOUBLE BARREL PIPE, w/ ½ Q IN EACH PIPE
100-YEAR FREQUENCY, w/ OUTLET CONDITION = HGL @ SOFFIT, REVISED DESIGN
PREPARED BY: TERRAIN ENGINEERING (PIMA2) 3/21/98

STATION	INVERT ELEV	DEPTH OF FLOW	W.S. ELEV	Q	VEL	VEL HEAD	ENERGY GRD.EL.	SUPER ELEV	CRITICAL DEPTH		HGT/ DIA	BASE/ ID NO.	ZL	NO PIER	AVBPR
L/ELEM	SO					SF AVE	HF			NORM DEPTH			ZR		
1000.00	1596.00	10.00	1606.00	1431.0	18.22	5.16	1611.16	.00	8.88		10.00	.00	.00	0	.00
158.00	.00184					.00997	1.58			10.00			.00		
1158.00	1596.29	11.29	1607.58	1431.0	18.22	5.16	1612.73	.00	8.88		10.00	.00	.00	0	.00
272.00	.00184					.00997	2.71			10.00			.00		
1430.00	1596.79	14.44	1611.23	1431.0	18.22	5.16	1616.39	.00	8.88		10.00	.00	.00	0	.00
110.00	.00191					.00997	1.10			10.00			.00		
1540.00	1597.00	15.59	1612.59	1431.0	18.22	5.16	1617.75	.00	8.88		10.00	.00	.00	0	.00
660.00	.00167					.00997	6.58			10.00			.00		
2200.00	1598.10	21.07	1619.17	1431.0	18.22	5.16	1624.33	.00	8.88		10.00	.00	.00	0	.00
NCT STR	.00000					.00970	.00						.00		
2200.00	1598.10	21.60	1619.70	1391.5	17.72	4.88	1624.58	.00	8.80		10.00	.00	.00	0	.00
420.00	.00190					.00943	3.96			10.00			.00		
2620.00	1598.90	25.00	1623.90	1391.5	17.72	4.88	1628.78	.00	8.80		10.00	.00	.00	0	.00
580.00	.02612					.00943	5.47			5.59			.00		
3200.00	1614.05	15.97	1630.02	1391.5	17.72	4.88	1634.90	.00	8.80		10.00	.00	.00	0	.00
JUNCT STR	.00000					.01074	.00						.00		
3200.00	1614.05	16.38	1630.43	1188.5	18.68	5.42	1635.86	.00	8.20		9.00	.00	.00	0	.00
50.75	.08125					.01206	.61			3.88			.00		
3250.75	1618.17	13.18	1631.35	1188.5	18.68	5.42	1636.78	.00	8.20		9.00	.00	.00	0	.00
HYDRAULIC JUMP													.00		
3250.75	1618.17	5.18	1623.35	1188.5	31.35	15.28	1638.63	.00	8.20		9.00	.00	.00	0	.00
22.09	.08125					.02866	.63			3.88			.00		

WATER SURFACE PROFILE LISTING

PIMA ROAD COLLECTOR CHANNEL - DOUBLE BARREL PIPE, w/ ½ Q IN EACH PIPE
100-YEAR FREQUENCY, w/ OUTLET CONDITION = HGL @ SOFFIT, REVISED DESIGN
PREPARED BY: TERRAIN ENGINEERING (PIMA2) 3/21/98

STATION	INVERT ELEV	DEPTH OF FLOW	W.S. ELEV	Q	VEL	VEL HEAD	ENERGY GRD.EL.	SUPER ELEV	CRITICAL DEPTH		HGT/ DIA	BASE/ ID NO.	ZL	NO PIER	AVBPR
L/ELEM	SO					SF AVE	HF			NORM DEPTH			ZR		
3272.85	1619.97	5.39	1625.35	1188.5	29.91	13.90	1639.26	.00	8.20		9.00	.00	.00	0	.00
18.66	.08125					.02538	.47			3.88			.00		
3291.51	1621.49	5.61	1627.09	1188.5	28.52	12.64	1639.73	.00	8.20		9.00	.00	.00	0	.00
15.55	.08125					.02250	.35			3.88			.00		
3307.06	1622.75	5.84	1628.59	1188.5	27.19	11.49	1640.08	.00	8.20		9.00	.00	.00	0	.00
12.94	.08125					.01998	.26			3.88			.00		
3320.00	1623.80	6.09	1629.89	1188.5	25.92	10.44	1640.34	.00	8.20		9.00	.00	.00	0	.00
360.00	.01917					.01840	6.62			6.05			.00		
3680.00	1630.70	6.20	1636.90	1188.5	25.45	10.06	1646.96	.00	8.20		9.00	.00	.00	0	.00
.00	.01917					.01798	.00			6.05			.00		
3680.00	1630.70	6.20	1636.90	1188.5	25.45	10.06	1646.96	.00	8.20		9.00	.00	.00	0	.00
167.37	.01849					.01781	2.98			6.13			.00		
3847.37	1633.79	6.24	1640.03	1188.5	25.25	9.91	1649.94	.00	8.20		9.00	.00	.00	0	.00
347.70	.01849					.01670	5.81			6.13			.00		
4195.06	1640.22	6.52	1646.74	1188.5	24.07	9.01	1655.75	.00	8.20		9.00	.00	.00	0	.00
144.94	.01849					.01495	2.17			6.13			.00		
4340.00	1642.90	6.83	1649.73	1188.5	22.95	8.19	1657.92	.00	8.20		9.00	.00	.00	0	.00
JUNCT STR	.00000					.01614	.00						.00		
4340.00	1642.90	5.94	1648.84	1125.5	25.29	9.94	1658.77	.00	8.06		9.00	.00	.00	0	.00
JUNCT STR	.00000					.01814	.00						.00		
4340.00	1642.90	5.94	1648.84	1125.5	25.29	9.94	1658.77	.00	8.06		9.00	.00	.00	0	.00
85.60	.01483					.01864	1.60			6.40			.00		

WATER SURFACE PROFILE LISTING

PIMA ROAD COLLECTOR CHANNEL - DOUBLE BARREL PIPE, w/ ½ Q IN EACH PIPE

100-YEAR FREQUENCY, w/ OUTLET CONDITION = HGL @ SOFFIT, REVISED DESIGN

PREPARED BY: TERRAIN ENGINEERING (PIMA2) 3/21/98

STATION	INVERT ELEV	DEPTH OF FLOW	W.S. ELEV	Q	VEL	VEL HEAD	ENERGY GRD.EL.	SUPER ELEV	CRITICAL DEPTH		HGT/ DIA	BASE/ ID NO.	ZL	NO PIER	AVBPR
L/ELEM	SO					SF AVE	HF			NORM DEPTH			ZR		
4425.60	1644.17	5.82	1649.99	1125.5	25.84	10.38	1660.37	.00	8.06		9.00	.00	.00	0	.00
145.23	.01483					.02036	2.96			6.40			.00		
4570.83	1646.32	5.59	1651.91	1125.5	27.10	11.42	1663.33	.00	8.06		9.00	.00	.00	0	.00
113.17	.01483					.02297	2.60			6.40			.00		
4684.00	1648.00	5.37	1653.37	1125.5	28.43	12.56	1665.93	.00	8.06		9.00	.00	.00	0	.00
.00	.01483					.02437	.00			6.40			.00		
4684.00	1648.00	5.37	1653.37	1125.5	28.43	12.56	1665.93	.00	8.06		9.00	.00	.00	0	.00
52.21	.03920					.02310	1.21			4.63			.00		
4736.21	1650.05	5.57	1655.62	1125.5	27.23	11.52	1667.13	.00	8.06		9.00	.00	.00	0	.00
43.80	.03920					.02059	.90			4.63			.00		
4780.01	1651.76	5.80	1657.57	1125.5	25.96	10.47	1668.04	.00	8.06		9.00	.00	.00	0	.00
33.65	.03920					.01828	.62			4.63			.00		
4813.66	1653.08	6.05	1659.13	1125.5	24.75	9.52	1668.65	.00	8.06		9.00	.00	.00	0	.00
26.13	.03920					.01627	.43			4.63			.00		
4839.79	1654.11	6.32	1660.42	1125.5	23.60	8.65	1669.08	.00	8.06		9.00	.00	.00	0	.00
20.21	.03920					.01452	.29			4.63			.00		
4860.00	1654.90	6.60	1661.50	1125.5	22.50	7.87	1669.37	.00	8.06		9.00	.00	.00	0	.00
17.33	.01054					.01380	.24			7.49			.00		
4877.33	1655.08	6.57	1661.65	1125.5	22.64	7.96	1669.61	.00	8.06		9.00	.00	.00	0	.00
122.02	.01054					.01473	1.80			7.49			.00		
4999.35	1656.37	6.28	1662.65	1125.5	23.74	8.76	1671.41	.00	8.06		9.00	.00	.00	0	.00
102.63	.01054					.01651	1.69			7.49			.00		

WATER SURFACE PROFILE LISTING

PIMA ROAD COLLECTOR CHANNEL - DOUBLE BARREL PIPE, w/ ½ Q IN EACH PIPE
100-YEAR FREQUENCY, w/ OUTLET CONDITION = HGL @ SOFFIT, REVISED DESIGN
PREPARED BY: TERRAIN ENGINEERING (PIMA2) 3/21/98

STATION	INVERT ELEV	DEPTH OF FLOW	W.S. ELEV	Q	VEL	VEL HEAD	ENERGY GRD.EL.	SUPER ELEV	CRITICAL DEPTH		HGT/ DIA	BASE/ ID NO.	ZL	NO PIER	AVBPR
L/ELEM	SO					SF AVE	HF			NORM DEPTH			ZR		
5101.99	1657.45	6.02	1663.47	1125.5	24.90	9.64	1673.10	.00	8.06		9.00	.00	.00	0	.00
89.44	.01054					.01856	1.66			7.49			.00		
5191.43	1658.39	5.77	1664.16	1125.5	26.12	10.60	1674.76	.00	8.06		9.00	.00	.00	0	.00
79.91	.01054					.02091	1.67			7.49			.00		
5271.34	1659.23	5.54	1664.77	1125.5	27.39	11.66	1676.43	.00	8.06		9.00	.00	.00	0	.00
72.66	.01054					.02360	1.71			7.49			.00		
5344.00	1660.00	5.32	1665.32	1125.5	28.73	12.82	1678.15	.00	8.06		9.00	.00	.00	0	.00
109.54	.03220					.02362	2.59			4.92			.00		
5453.54	1663.53	5.54	1669.07	1125.5	27.40	11.67	1680.74	.00	8.06		9.00	.00	.00	0	.00
73.75	.03220					.02094	1.54			4.92			.00		
5527.29	1665.90	5.77	1671.67	1125.5	26.13	10.61	1682.28	.00	8.06		9.00	.00	.00	0	.00
52.71	.03220					.01858	.98			4.92			.00		
5580.00	1667.60	6.01	1673.61	1125.5	24.91	9.64	1683.26	.00	8.06		9.00	.00	.00	0	.00
142.95	.01651					.01776	2.54			6.14			.00		
5722.95	1669.96	5.95	1675.91	1125.5	25.23	9.89	1685.80	.00	8.06		9.00	.00	.00	0	.00
281.05	.01651					.01917	5.39			6.14			.00		
6004.00	1674.60	5.71	1680.31	1125.5	26.46	10.88	1691.19	.00	8.06		9.00	.00	.00	0	.00
6.50	.02030					.02031	.13			5.71			.00		
6010.50	1674.73	5.71	1680.44	1125.5	26.46	10.88	1691.32	.00	8.06		9.00	.00	.00	0	.00
653.50	.02030					.02076	13.57			5.71			.00		
6664.00	1688.00	5.62	1693.62	1125.5	26.92	11.26	1704.88	.00	8.06		9.00	.00	.00	0	.00
660.00	.02121					.02061	13.60			5.62			.00		

WATER SURFACE PROFILE LISTING

PIMA ROAD COLLECTOR CHANNEL - DOUBLE BARREL PIPE, w/ ½ Q IN EACH PIPE
100-YEAR FREQUENCY, w/ OUTLET CONDITION = HGL @ SOFFIT, REVISED DESIGN
PREPARED BY: TERRAIN ENGINEERING (PIMA2) 3/21/98

STATION / L/ELEM	INVERT ELEV / SO	DEPTH OF FLOW	W.S. ELEV	Q	VEL	VEL HEAD / SF AVE	ENERGY GRD.EL. / HF	SUPER ELEV	CRITICAL DEPTH / NORM DEPTH	HGT/ DIA	BASE/ ID NO.	ZL / ZR	NO PIER	AVBPR
7324.00	1702.00	5.74	1707.74	1125.5	26.30	10.75	1718.49	.00	8.06	9.00	.00	.00	0	.00
.00	.02121					.02001	.00		5.62			.00		
7324.00	1702.00	5.74	1707.74	1125.5	26.30	10.75	1718.49	.00	8.06	9.00	.00	.00	0	.00
168.67	.01849					.02053	3.46		5.90			.00		
7492.67	1705.12	5.64	1710.75	1125.5	26.84	11.20	1721.95	.00	8.06	9.00	.00	.00	0	.00
228.19	.01849					.02241	5.11		5.90			.00		
7720.86	1709.34	5.41	1714.75	1125.5	28.15	12.32	1727.07	.00	8.06	9.00	.00	.00	0	.00
149.41	.01849					.02532	3.78		5.90			.00		
7870.27	1712.10	5.20	1717.30	1125.5	29.53	13.55	1730.85	.00	8.06	9.00	.00	.00	0	.00
113.73	.01849					.02865	3.26		5.90			.00		
7984.00	1714.20	5.01	1719.21	1125.5	30.97	14.90	1734.11	.00	8.06	9.00	.00	.00	0	.00
47.18	.01887					.03133	1.48		5.85			.00		
8031.18	1715.09	4.92	1720.01	1125.5	31.66	15.58	1735.59	.00	8.06	9.00	.00	.00	0	.00
88.46	.01887					.03440	3.04		5.85			.00		
8119.64	1716.76	4.73	1721.49	1125.5	33.21	17.14	1738.63	.00	8.06	9.00	.00	.00	0	.00
76.36	.01887					.03902	2.98		5.85			.00		
8196.00	1718.20	4.56	1722.76	1125.5	34.83	18.85	1741.61	.00	8.06	9.00	.00	.00	0	.00
-.00	.01887					.02305	.00		5.85			.00		
8196.00	1718.20	4.56	1722.76	1125.5	34.83	18.85	1741.61	.00	8.06	9.00	.00	.00	0	.00
.89	.02523					.00461	.00		2.86			.00		
8196.89	1718.22	4.56	1722.78	1125.5	34.81	18.83	1741.61	.00	8.06	9.00	.00	.00	0	.00
73.56	.02523					.00433	.32		2.86			.00		

WATER SURFACE PROFILE LISTING

PIMA ROAD COLLECTOR CHANNEL - DOUBLE BARREL PIPE, w/ ½ Q IN EACH PIPE
100-YEAR FREQUENCY, w/ OUTLET CONDITION = HGL @ SOFFIT, REVISED DESIGN
PREPARED BY: TERRAIN ENGINEERING (PIMA2) 3/21/98

STATION	INVERT ELEV	DEPTH OF FLOW	W.S. ELEV	Q	VEL	VEL HEAD	ENERGY GRD.EL.	SUPER ELEV	CRITICAL DEPTH		HGT/ DIA	BASE/ ID NO.	ZL	NO PIER	AVBPR
L/ELEM	SO					SF AVE	HF			NORM DEPTH			ZR		
8270.46	1720.08	4.73	1724.81	1125.5	33.19	17.12	1741.93	.00	8.06		9.00	.00	.00	0	.00
64.11	.02523					.00382	.24			2.86			.00		
8334.57	1721.70	4.92	1726.61	1125.5	31.65	15.56	1742.18	.00	8.06		9.00	.00	.00	0	.00
55.82	.02523					.00337	.19			2.86			.00		
8390.38	1723.10	5.11	1728.22	1125.5	30.17	14.15	1742.36	.00	8.06		9.00	.00	.00	0	.00
48.65	.02523					.00298	.14			2.86			.00		
8439.03	1724.33	5.32	1729.65	1125.5	28.77	12.86	1742.51	.00	8.06		9.00	.00	.00	0	.00
42.15	.02523					.00263	.11			2.86			.00		
8481.18	1725.39	5.53	1730.93	1125.5	27.43	11.69	1742.62	.00	8.06		9.00	.00	.00	0	.00
36.39	.02523					.00233	.08			2.86			.00		
8517.57	1726.31	5.76	1732.07	1125.5	26.15	10.63	1742.71	.00	8.06		9.00	.00	.00	0	.00
31.11	.02523					.00207	.06			2.86			.00		
8548.69	1727.10	6.01	1733.11	1125.5	24.94	9.66	1742.77	.00	8.06		9.00	.00	.00	0	.00
26.33	.02523					.00184	.05			2.86			.00		
8575.01	1727.76	6.27	1734.03	1125.5	23.78	8.79	1742.82	.00	8.06		9.00	.00	.00	0	.00
21.87	.02523					.00164	.04			2.86			.00		
8596.88	1728.31	6.56	1734.87	1125.5	22.67	7.99	1742.85	.00	8.06		9.00	.00	.00	0	.00
17.52	.02523					.00147	.03			2.86			.00		
8614.40	1728.75	6.87	1735.62	1125.5	21.62	7.26	1742.88	.00	8.06		9.00	.00	.00	0	.00
13.31	.02523					.00132	.02			2.86			.00		
8627.71	1729.09	7.21	1736.30	1125.5	20.61	6.60	1742.90	.00	8.06		9.00	.00	.00	0	.00
8.87	.02523					.00120	.01			2.86			.00		

WATER SURFACE PROFILE LISTING

PIMA ROAD COLLECTOR CHANNEL - DOUBLE BARREL PIPE, w/ ½ Q IN EACH PIPE
100-YEAR FREQUENCY, w/ OUTLET CONDITION = HGL @ SOFFIT, REVISED DESIGN
PREPARED BY: TERRAIN ENGINEERING (PIMA2) 3/21/98

STATION	INVERT ELEV	DEPTH OF FLOW	W.S. ELEV	Q	VEL	VEL HEAD	ENERGY GRD.EL.	SUPER ELEV	CRITICAL DEPTH		HGT/ DIA	BASE/ ID NO.	ZL	NO PIER	AVBPR
L/ELEM	SO					SF AVE	HF			NORM DEPTH			ZR		
8636.57	1729.31	7.59	1736.91	1125.5	19.65	6.00	1742.91	.00	8.06		9.00	.00	.00	0	.00
3.43	.02523					.00110	.00			2.86			.00		
8640.00	1729.40	8.06	1737.46	1125.5	18.73	5.45	1742.91	.00	8.06		9.00	.00	.00	0	.00
NCT STR	.02499					.00919	.04						.00		
8644.00	1729.50	10.21	1739.71	1016.5	15.98	3.97	1743.68	.00	7.77		9.00	.00	.00	0	.00
ANS STR	.19200					.00673	.34						.00		
8694.00	1739.10	4.07	1743.17	1016.5	8.52	1.13	1744.30	.00	3.29		4.00	31.50	.00	2	.75
71.14	.00563					.00464	.33			3.00			.00		
8765.14	1739.50	4.00	1743.50	1016.5	8.52	1.13	1744.63	.00	3.29		4.00	31.50	.00	2	.75
25.48	.00563					.00273	.07			3.00			.00		
8790.62	1739.64	3.81	1743.46	1016.5	8.89	1.23	1744.68	.00	3.29		4.00	31.50	.00	2	.75
21.49	.00563					.00308	.07			3.00			.00		
8812.11	1739.76	3.64	1743.40	1016.5	9.32	1.35	1744.75	.00	3.29		4.00	31.50	.00	2	.75
15.06	.00563					.00349	.05			3.00			.00		
8827.17	1739.85	3.48	1743.33	1016.5	9.73	1.47	1744.80	.00	3.29		4.00	31.50	.00	2	.75
HYDRAULIC JUMP													.00		
8827.17	1739.85	3.11	1742.96	1016.5	10.90	1.85	1744.80	.00	3.29		4.00	31.50	.00	2	.75
15.06	.00563					.00502	.08			3.00			.00		
8842.23	1739.93	3.14	1743.07	1016.5	10.80	1.81	1744.88	.00	3.29		4.00	31.50	.00	2	.75
11.77	.00563					.00464	.05			3.00			.00		
8854.00	1740.00	3.29	1743.29	1016.5	10.29	1.65	1744.94	.00	3.29		4.00	31.50	.00	2	.75

STORM DRAIN ANALYSIS PLUS

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rsion 1.20
rial Number 07010175

Mar 22, 1998 10:27:33

put file : PIMA3.DAT
Output file: PIMA3.OUT

INPUT FILE LISTING

PIMA ROAD COLLECTOR CHANNEL - DOUBLE BARREL PIPE, w/ ½ Q IN EACH PIPE
T2 100-YEAR FREQUENCY, w/ OUTLET CONDITION = HGL @ SOFFIT, ALTERNATE DESIGN
PREPARED BY: TERRAIN ENGINEERING (PIMA3) 3/21/98

	1000.001596.00120		015		1606.00		
R	1158.001596.29120		015				
R	1430.001596.79120		015			76.0	
	1540.001597.00120		015				1
	2200.001598.10120		015				
JX	2200.001598.10120	54	015	39.5	1500.85	30.0	
R	2620.001598.90120		015				1
	3200.001614.05120		015			40.0	
	3200.001614.05108	66	015	203.00	1616.30	30.0	
R	3320.001623.80108		015			40.0	
R	3680.001630.70108		015				1
	4340.001642.90108		015				
JX	4340.001642.90108	60	015	63.0	1645.15	30.0	
R	4684.001648.00108		015				1
	4860.001654.90108		015				
	5341.501659.97108		015				
TS	5346.501660.08	96	015				
R	5580.001667.60	96	015				
	6004.001674.60	96	015				1
	6664.001688.00	96	015				1
R	7324.001702.00	96	015				1
R	7984.001714.20	96	015				
	8193.501718.14	96	015				
	8198.501718.26108		015				
R	8307.001721.00108		015				
R	8621.001728.92108		015			90.00	
	8640.001729.40108		005				
JX	8644.001729.50108	66	015	109.0	1631.25	30.00	
TS	8694.001739.10	1	015				
	8854.001740.00	1	015				
		1	015				

RD CODE	SECT NO	CHN TYPE	NO OF PIERS	AVE PIER WIDTH	HEIGHT 1 DIAMETER	BASE WIDTH	ZL	ZR	INV DROP	Y(1)	Y(2)	Y(3)	Y(4)	Y(5)	Y(6)	Y(7)	Y(8)	Y(9)	Y(10)
	1	3	2	.75	4.00	31.50	.00	.00	.00										
	54	4			4.50														
CD	60	4			5.00														
CD	66	4			5.50														
	96	4			8.00														
	108	4			9.00														
CD	114	4			9.50														
CD	120	4			10.00														

WATER SURFACE PROFILE - ELEMENT CARD LISTING

```
ELEMENT NO   1 IS A SYSTEM OUTLET      *        *     *
                U/S DATA   STATION    INVERT  SECT                                W S ELEV
                            1000.00 1596.00  120                                  1606.00

ELEMENT NO   2 IS A REACH              *        *     *
                U/S DATA   STATION    INVERT  SECT              N                RADIUS  ANGLE  ANG PT  MAN H
                            1158.00 1596.29  120              .015                  .00    .00     .00     0

ELEMENT NO   3 IS A REACH              *        *     *
                U/S DATA   STATION    INVERT  SECT              N                RADIUS  ANGLE  ANG PT  MAN H
                            1430.00 1596.79  120              .015                  .00  76.00     .00     0

ELEMENT NO   4 IS A REACH              *        *     *
                U/S DATA   STATION    INVERT  SECT              N                RADIUS  ANGLE  ANG PT  MAN H
                            1540.00 1597.00  120              .015                  .00    .00     .00     1

ELEMENT NO   5 IS A REACH              *        *     *
                U/S DATA   STATION    INVERT  SECT              N                RADIUS  ANGLE  ANG PT  MAN H
                            2200.00 1598.10  120              .015                  .00    .00     .00     0

ELEMENT NO   6 IS A JUNCTION           *        *     *     *                *                *              *
                U/S DATA   STATION    INVERT  SECT LAT-1 LAT-2   N      Q3       Q4    INVERT-3 INVERT-4  PHI 3   PHI 4
                            2200.00 1598.10  120    54     0   .015     39.5       .0  1500.85      .00  30.00     .00
THE ABOVE ELEMENT CONTAINED AN INVERT ELEV WHICH WAS NOT GREATER THAN THE PREVIOUS INVERT ELEV -WARNING
THE ABOVE ELEMENT CONTAINED AN INVERT ELEV WHICH WAS NOT GREATER THAN THE PREVIOUS INVERT ELEV -WARNING

ELEMENT NO   7 IS A REACH              *        *     *
                U/S DATA   STATION    INVERT  SECT              N                RADIUS  ANGLE  ANG PT  MAN H
                            2620.00 1598.90  120              .015                  .00    .00     .00     1

ELEMENT NO   8 IS A REACH              *        *     *
                U/S DATA   STATION    INVERT  SECT              N                RADIUS  ANGLE  ANG PT  MAN H
                            3200.00 1614.05  120              .015                  .00  40.00     .00     0

ELEMENT NO   9 IS A JUNCTION           *        *     *     *                *                *              *
                U/S DATA   STATION    INVERT  SECT LAT-1 LAT-2   N      Q3       Q4    INVERT-3 INVERT-4  PHI 3   PHI 4
                            3200.00 1614.05  108    66     0   .015    203.0       .0  1616.30      .00  30.00     .00
THE ABOVE ELEMENT CONTAINED AN INVERT ELEV WHICH WAS NOT GREATER THAN THE PREVIOUS INVERT ELEV -WARNING
THE ABOVE ELEMENT CONTAINED AN INVERT ELEV WHICH WAS NOT GREATER THAN THE PREVIOUS INVERT ELEV -WARNING

ELEMENT NO  10 IS A REACH              *        *     *
                U/S DATA   STATION    INVERT  SECT              N                RADIUS  ANGLE  ANG PT  MAN H
                            3320.00 1623.80  108              .015                  .00  40.00     .00     0
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WATER SURFACE PROFILE - ELEMENT CARD LISTING

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ELEMENT NO  11 IS A REACH            *        *     *
                U/S DATA   STATION    INVERT  SECT              N                                RADIUS  ANGLE  ANG PT  MAN H
                            3680.00 1630.70  108              .015                                  .00    .00     .00      1

ELEMENT NO  12 IS A REACH            *        *     *
                U/S DATA   STATION    INVERT  SECT              N                                RADIUS  ANGLE  ANG PT  MAN H
                            4340.00 1642.90  108              .015                                  .00    .00     .00      0

ELEMENT NO  13 IS A JUNCTION         *        *     *     *                 *                 *              *
                U/S DATA   STATION    INVERT  SECT LAT-1 LAT-2   N      Q3       Q4    INVERT-3 INVERT-4  PHI 3   PHI 4
                            4340.00 1642.90  108    60     0   .015    63.0       .0  1645.15      .00  30.00     .00
E ABOVE ELEMENT CONTAINED AN INVERT ELEV WHICH WAS NOT GREATER THAN THE PREVIOUS INVERT ELEV -WARNING
THE ABOVE ELEMENT CONTAINED AN INVERT ELEV WHICH WAS NOT GREATER THAN THE PREVIOUS INVERT ELEV -WARNING

LEMENT NO  14 IS A REACH             *        *     *
                U/S DATA   STATION    INVERT  SECT              N                                RADIUS  ANGLE  ANG PT  MAN H
                            4684.00 1648.00  108              .015                                  .00    .00     .00      1

LEMENT NO  15 IS A REACH             *        *     *
                U/S DATA   STATION    INVERT  SECT              N                                RADIUS  ANGLE  ANG PT  MAN H
                            4860.00 1654.90  108              .015                                  .00    .00     .00      0

EMENT NO  16 IS A REACH              *        *     *
                U/S DATA   STATION    INVERT  SECT              N                                RADIUS  ANGLE  ANG PT  MAN H
                            5341.50 1659.97  108              .015                                  .00    .00     .00      0

EMENT NO  17 IS A TRANSITION         *        *     *
                U/S DATA   STATION    INVERT  SECT              N
                            5346.50 1660.08   96              .015

EMENT NO  18 IS A REACH              *        *     *
                U/S DATA   STATION    INVERT  SECT              N                                RADIUS  ANGLE  ANG PT  MAN H
                            5580.00 1667.60   96              .015                                  .00    .00     .00      0

ELEMENT NO  19 IS A REACH            *        *     *
                U/S DATA   STATION    INVERT  SECT              N                                RADIUS  ANGLE  ANG PT  MAN H
                            6004.00 1674.60   96              .015                                  .00    .00     .00      1

ELEMENT NO  20 IS A REACH            *        *     *
                U/S DATA   STATION    INVERT  SECT              N                                RADIUS  ANGLE  ANG PT  MAN H
                            6664.00 1688.00   96              .015                                  .00    .00     .00      1

ELEMENT NO  21 IS A REACH            *        *     *
                U/S DATA   STATION    INVERT  SECT              N                                RADIUS  ANGLE  ANG PT  MAN H
                            7324.00 1702.00   96              .015                                  .00    .00     .00      1

ELEMENT NO  22 IS A REACH            *        *     *
                U/S DATA   STATION    INVERT  SECT              N                                RADIUS  ANGLE  ANG PT  MAN H
                            7984.00 1714.20   96              .015                                  .00    .00     .00      0
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WATER SURFACE PROFILE - ELEMENT CARD LISTING

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ELEMENT NO  23 IS A REACH            *        *    *
                U/S DATA   STATION    INVERT  SECT              N                                RADIUS  ANGLE  ANG PT  MAN H
                            8193.50 1718.14   96              .015                                  .00    .00     .00      0

ELEMENT NO  24 IS A TRANSITION       *        *    *
                U/S DATA   STATION    INVERT  SECT              N
                            8198.50 1718.26  108              .015

ELEMENT NO  25 IS A REACH            *        *    *
                U/S DATA   STATION    INVERT  SECT              N                                RADIUS  ANGLE  ANG PT  MAN H
                            8307.00 1721.00  108              .015                                  .00    .00     .00      0

ELEMENT NO  26 IS A REACH            *        *    *
                U/S DATA   STATION    INVERT  SECT              N                                RADIUS  ANGLE  ANG PT  MAN H
                            8621.00 1728.92  108              .015                                  .00  90.00     .00      0

ELEMENT NO  27 IS A REACH            *        *    *
                U/S DATA   STATION    INVERT  SECT              N                                RADIUS  ANGLE  ANG PT  MAN H
                            8640.00 1729.40  108              .005                                  .00    .00     .00      0

ELEMENT NO  28 IS A JUNCTION         *        *    *    *                *                 *              *
                U/S DATA   STATION    INVERT  SECT LAT-1 LAT-2  N      Q3       Q4    INVERT-3 INVERT-4  PHI 3   PHI 4
                            8644.00 1729.50  108    66     0  .015    109.0       .0  1631.25      .00  30.00     .00

ELEMENT NO  29 IS A TRANSITION       *        *    *
                U/S DATA   STATION    INVERT  SECT              N
                            8694.00 1739.10    1              .015

ELEMENT NO  30 IS A REACH            *        *    *
                U/S DATA   STATION    INVERT  SECT              N                                RADIUS  ANGLE  ANG PT  MAN H
                            8854.00 1740.00    1              .015                                  .00    .00     .00      0

ELEMENT NO  31 IS A SYSTEM HEADWORKS                 *                    *
                U/S DATA   STATION    INVERT  SECT                                   W S ELEV
                            8854.00 1740.00    1                                        .00
NO EDIT ERRORS ENCOUNTERED-COMPUTATION IS NOW BEGINNING

 WARNING NO. 2 ** - WATER SURFACE ELEVATION GIVEN IS LESS THAN OR EQUALS INVERT ELEVATION IN HDWKDS, W.S.ELEV = INV + DC
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WATER SURFACE PROFILE LISTING

PIMA ROAD COLLECTOR CHANNEL - DOUBLE BARREL PIPE, w/ ½ Q IN EACH PIPE
100-YEAR FREQUENCY, w/ OUTLET CONDITION = HGL @ SOFFIT, ALTERNATE DESIGN
PREPARED BY: TERRAIN ENGINEERING (PIMA3) 3/21/98

STATION	INVERT ELEV	DEPTH OF FLOW	W.S. ELEV	Q	VEL	VEL HEAD	ENERGY GRD.EL.	SUPER ELEV	CRITICAL DEPTH		HGT/ DIA	BASE/ ID NO.	ZL	NO PIER	AVBPR
L/ELEM	SO					SF AVE	HF			NORM DEPTH			ZR		
1000.00	1596.00	10.00	1606.00	1431.0	18.22	5.16	1611.16	.00	8.88		10.00	.00	.00	0	.00
158.00	.00184					.00997	1.58			10.00			.00		
1158.00	1596.29	11.29	1607.58	1431.0	18.22	5.16	1612.73	.00	8.88		10.00	.00	.00	0	.00
272.00	.00184					.00997	2.71			10.00			.00		
1430.00	1596.79	14.44	1611.23	1431.0	18.22	5.16	1616.39	.00	8.88		10.00	.00	.00	0	.00
110.00	.00191					.00997	1.10			10.00			.00		
1540.00	1597.00	15.59	1612.59	1431.0	18.22	5.16	1617.75	.00	8.88		10.00	.00	.00	0	.00
660.00	.00167					.00997	6.58			10.00			.00		
2200.00	1598.10	21.07	1619.17	1431.0	18.22	5.16	1624.33	.00	8.88		10.00	.00	.00	0	.00
JUNCT STR	.00000					.00970	.00						.00		
2200.00	1598.10	21.60	1619.70	1391.5	17.72	4.88	1624.58	.00	8.80		10.00	.00	.00	0	.00
420.00	.00190					.00943	3.96			10.00			.00		
2620.00	1598.90	25.00	1623.90	1391.5	17.72	4.88	1628.78	.00	8.80		10.00	.00	.00	0	.00
580.00	.02612					.00943	5.47			5.59			.00		
3200.00	1614.05	15.97	1630.02	1391.5	17.72	4.88	1634.90	.00	8.80		10.00	.00	.00	0	.00
JUNCT STR	.00000					.01074	.00						.00		
3200.00	1614.05	16.38	1630.43	1188.5	18.68	5.42	1635.86	.00	8.20		9.00	.00	.00	0	.00
50.76	.08125					.01206	.61			3.88			.00		
3250.76	1618.17	13.18	1631.35	1188.5	18.68	5.42	1636.78	.00	8.20		9.00	.00	.00	0	.00
HYDRAULIC JUMP													.00		
3250.76	1618.17	5.18	1623.35	1188.5	31.35	15.28	1638.63	.00	8.20		9.00	.00	.00	0	.00
22.08	.08125					.02866	.63			3.88			.00		

WATER SURFACE PROFILE LISTING

PIMA ROAD COLLECTOR CHANNEL - DOUBLE BARREL PIPE, w/ ½ Q IN EACH PIPE

100-YEAR FREQUENCY, w/ OUTLET CONDITION = HGL @ SOFFIT, ALTERNATE DESIGN

PREPARED BY: TERRAIN ENGINEERING (PIMA3) 3/21/98

STATION	INVERT ELEV	DEPTH OF FLOW	W.S. ELEV	Q	VEL	VEL HEAD	ENERGY GRD.EL.	SUPER ELEV	CRITICAL DEPTH		HGT/ DIA	BASE/ ID NO.	ZL	NO PIER	AVBPR
L/ELEM	SO					SF AVE	HF			NORM DEPTH			ZR		
3272.84	1619.97	5.39	1625.35	1188.5	29.91	13.90	1639.26	.00	8.20		9.00	.00	.00	0	.00
18.66	.08125					.02538	.47			3.88			.00		
3291.50	1621.48	5.61	1627.09	1188.5	28.52	12.64	1639.73	.00	8.20		9.00	.00	.00	0	.00
15.55	.08125					.02250	.35			3.88			.00		
3307.06	1622.75	5.84	1628.59	1188.5	27.19	11.49	1640.08	.00	8.20		9.00	.00	.00	0	.00
12.94	.08125					.01998	.26			3.88			.00		
3320.00	1623.80	6.09	1629.89	1188.5	25.92	10.44	1640.34	.00	8.20		9.00	.00	.00	0	.00
360.00	.01917					.01840	6.62			6.05			.00		
3680.00	1630.70	6.20	1636.90	1188.5	25.45	10.07	1646.96	.00	8.20		9.00	.00	.00	0	.00
164.21	.01849					.01782	2.93			6.13			.00		
3844.21	1633.74	6.24	1639.97	1188.5	25.26	9.91	1649.89	.00	8.20		9.00	.00	.00	0	.00
350.28	.01849					.01671	5.85			6.13			.00		
4194.48	1640.21	6.52	1646.73	1188.5	24.08	9.01	1655.74	.00	8.20		9.00	.00	.00	0	.00
145.52	.01849					.01496	2.18			6.13			.00		
4340.00	1642.90	6.82	1649.72	1188.5	22.96	8.19	1657.92	.00	8.20		9.00	.00	.00	0	.00
JUNCT STR	.00000					.01615	.00						.00		
4340.00	1642.90	5.93	1648.83	1125.5	25.29	9.94	1658.78	.00	8.06		9.00	.00	.00	0	.00
86.25	.01483					.01866	1.61			6.40			.00		
4426.25	1644.18	5.82	1650.00	1125.5	25.85	10.39	1660.39	.00	8.06		9.00	.00	.00	0	.00
144.80	.01483					.02038	2.95			6.40			.00		
4571.06	1646.33	5.59	1651.91	1125.5	27.11	11.42	1663.34	.00	8.06		9.00	.00	.00	0	.00
112.94	.01483					.02300	2.60			6.40			.00		

WATER SURFACE PROFILE LISTING

PIMA ROAD COLLECTOR CHANNEL - DOUBLE BARREL PIPE, w/ ½ Q IN EACH PIPE
100-YEAR FREQUENCY, w/ OUTLET CONDITION = HGL @ SOFFIT, ALTERNATE DESIGN
PREPARED BY: TERRAIN ENGINEERING (PIMA3) 3/21/98

STATION	INVERT ELEV	DEPTH OF FLOW	W.S. ELEV	Q	VEL	VEL HEAD	ENERGY GRD.EL.	SUPER ELEV	CRITICAL DEPTH		HGT/ DIA	BASE/ ID NO.	ZL	NO PIER	AVBPR
L/ELEM	SO					SF AVE	HF			NORM DEPTH			ZR		
4684.00	1648.00	5.37	1653.37	1125.5	28.44	12.57	1665.94	.00	8.06		9.00	.00	.00	0	.00
51.43	.03920					.02314	1.19			4.63			.00		
4735.43	1650.02	5.56	1655.58	1125.5	27.26	11.55	1667.13	.00	8.06		9.00	.00	.00	0	.00
44.08	.03920					.02065	.91			4.63			.00		
4779.50	1651.74	5.80	1657.54	1125.5	25.99	10.50	1668.04	.00	8.06		9.00	.00	.00	0	.00
33.84	.03920					.01834	.62			4.63			.00		
4813.34	1653.07	6.04	1659.11	1125.5	24.78	9.54	1668.66	.00	8.06		9.00	.00	.00	0	.00
26.32	.03920					.01632	.43			4.63			.00		
4839.67	1654.10	6.31	1660.41	1125.5	23.63	8.67	1669.09	.00	8.06		9.00	.00	.00	0	.00
20.33	.03920					.01456	.30			4.63			.00		
4860.00	1654.90	6.60	1661.50	1125.5	22.53	7.89	1669.38	.00	8.06		9.00	.00	.00	0	.00
16.00	.01053					.01383	.22			7.49			.00		
4876.00	1655.07	6.56	1661.63	1125.5	22.65	7.97	1669.60	.00	8.06		9.00	.00	.00	0	.00
121.69	.01053					.01475	1.79			7.49			.00		
4997.70	1656.35	6.28	1662.63	1125.5	23.75	8.77	1671.40	.00	8.06		9.00	.00	.00	0	.00
102.28	.01053					.01653	1.69			7.49			.00		
5099.97	1657.43	6.01	1663.44	1125.5	24.91	9.65	1673.09	.00	8.06		9.00	.00	.00	0	.00
89.21	.01053					.01858	1.66			7.49			.00		
5189.18	1658.37	5.77	1664.13	1125.5	26.13	10.61	1674.74	.00	8.06		9.00	.00	.00	0	.00
79.83	.01053					.02094	1.67			7.49			.00		
5269.01	1659.21	5.54	1664.74	1125.5	27.41	11.67	1676.42	.00	8.06		9.00	.00	.00	0	.00
72.49	.01053					.02364	1.71			7.49			.00		

WATER SURFACE PROFILE LISTING

PIMA ROAD COLLECTOR CHANNEL - DOUBLE BARREL PIPE, w/ ½ Q IN EACH PIPE
100-YEAR FREQUENCY, w/ OUTLET CONDITION = HGL @ SOFFIT, ALTERNATE DESIGN
PREPARED BY: TERRAIN ENGINEERING (PIMA3) 3/21/98

STATION	INVERT ELEV	DEPTH OF FLOW	W.S. ELEV	Q	VEL	VEL HEAD	ENERGY GRD.EL.	SUPER ELEV	CRITICAL DEPTH		HGT/ DIA	BASE/ ID NO.	ZL	NO PIER	AVBPR
L/ELEM	SO					SF AVE	HF			NORM DEPTH			ZR		
5341.50	1659.97	5.32	1665.29	1125.5	28.74	12.84	1678.13	.00	8.06		9.00	.00	.00	0	.00
ANS STR	.02200					.02502	.13						.00		
5346.50	1660.08	5.94	1666.02	1125.5	28.13	12.29	1678.31	.00	7.69		8.00	.00	.00	0	.00
1.85	.03221					.02495	.05			5.38			.00		
5348.35	1660.14	5.94	1666.08	1125.5	28.11	12.28	1678.36	.00	7.69		8.00	.00	.00	0	.00
97.14	.03221					.02367	2.30			5.38			.00		
5445.49	1663.27	6.23	1669.50	1125.5	26.80	11.16	1680.66	.00	7.69		8.00	.00	.00	0	.00
64.15	.03221					.02136	1.37			5.38			.00		
5509.65	1665.33	6.55	1671.88	1125.5	25.55	10.14	1682.03	.00	7.69		8.00	.00	.00	0	.00
43.45	.03221					.01947	.85			5.38			.00		
5553.09	1666.73	6.92	1673.65	1125.5	24.36	9.22	1682.87	.00	7.69		8.00	.00	.00	0	.00
26.91	.03221					.01811	.49			5.38			.00		
5580.00	1667.60	7.38	1674.98	1125.5	23.23	8.38	1683.36	.00	7.69		8.00	.00	.00	0	.00
236.57	.01651					.01810	4.28			8.00			.00		
5816.57	1671.51	6.92	1678.43	1125.5	24.35	9.22	1687.64	.00	7.69		8.00	.00	.00	0	.00
187.43	.01651					.01946	3.65			8.00			.00		
6004.00	1674.60	6.55	1681.15	1125.5	25.54	10.14	1691.29	.00	7.69		8.00	.00	.00	0	.00
660.00	.02030					.02061	13.60			6.55			.00		
6664.00	1688.00	6.45	1694.45	1125.5	25.93	10.45	1704.89	.00	7.69		8.00	.00	.00	0	.00
378.97	.02121					.02051	7.77			6.40			.00		
7042.97	1696.04	6.59	1702.62	1125.5	25.42	10.04	1712.67	.00	7.69		8.00	.00	.00	0	.00
281.03	.02121					.01930	5.42			6.40			.00		

WATER SURFACE PROFILE LISTING

PIMA ROAD COLLECTOR CHANNEL - DOUBLE BARREL PIPE, w/ ½ Q IN EACH PIPE
100-YEAR FREQUENCY, w/ OUTLET CONDITION = HGL @ SOFFIT, ALTERNATE DESIGN
PREPARED BY: TERRAIN ENGINEERING (PIMA3) 3/21/98

STATION	INVERT ELEV	DEPTH OF FLOW	W.S. ELEV	Q	VEL	VEL HEAD	ENERGY GRD.EL.	SUPER ELEV	CRITICAL DEPTH		HGT/ DIA	BASE/ ID NO.	ZL	NO PIER	AVBPR
L/ELEM	SO					SF AVE	HF			NORM DEPTH			ZR		
7324.00	1702.00	6.96	1708.96	1125.5	24.24	9.13	1718.09	.00	7.69		8.00	.00	.00	0	.00
660.00	.01849					.01915	12.64			6.96			.00		
7984.00	1714.20	6.64	1720.84	1125.5	25.22	9.89	1730.73	.00	7.69		8.00	.00	.00	0	.00
209.50	.01881					.02028	4.25			6.87			.00		
8193.50	1718.14	6.47	1724.61	1125.5	25.83	10.37	1734.98	.00	7.69		8.00	.00	.00	0	.00
ANS STR	.02400					.02123	.11						.00		
8198.50	1718.26	5.58	1723.84	1125.5	27.16	11.47	1735.31	.00	8.06		9.00	.00	.00	0	.00
108.50	.02525					.02101	2.28			5.31			.00		
8307.00	1721.00	5.71	1726.71	1125.5	26.46	10.88	1737.59	.00	8.06		9.00	.00	.00	0	.00
.00	.02525					.02032	.00			5.31			.00		
8307.00	1721.00	5.71	1726.71	1125.5	26.46	10.88	1737.59	.00	8.06		9.00	.00	.00	0	.00
93.67	.02522					.01950	1.83			5.31			.00		
8400.67	1723.36	5.87	1729.24	1125.5	25.59	10.18	1739.42	.00	8.06		9.00	.00	.00	0	.00
88.86	.02522					.01766	1.57			5.31			.00		
8489.53	1725.60	6.13	1731.73	1125.5	24.40	9.25	1740.98	.00	8.06		9.00	.00	.00	0	.00
59.93	.02522					.01572	.94			5.31			.00		
8549.46	1727.12	6.40	1733.51	1125.5	23.27	8.41	1741.93	.00	8.06		9.00	.00	.00	0	.00
42.04	.02522					.01405	.59			5.31			.00		
8591.50	1728.18	6.69	1734.87	1125.5	22.18	7.65	1742.52	.00	8.06		9.00	.00	.00	0	.00
29.50	.02522					.01260	.37			5.31			.00		
8621.00	1728.92	7.02	1735.94	1125.5	21.15	6.95	1742.89	.00	8.06		9.00	.00	.00	0	.00
6.72	.02526					.00129	.01			2.86			.00		

WATER SURFACE PROFILE LISTING
PIMA ROAD COLLECTOR CHANNEL - DOUBLE BARREL PIPE, w/ ½ Q IN EACH PIPE
100-YEAR FREQUENCY, w/ OUTLET CONDITION = HGL @ SOFFIT, ALTERNATE DESIGN
PREPARED BY: TERRAIN ENGINEERING (PIMA3) 3/21/98

STATION	INVERT ELEV	DEPTH OF FLOW	W.S. ELEV	Q	VEL	VEL HEAD	ENERGY GRD.EL.	SUPER ELEV	CRITICAL DEPTH		HGT/ DIA	BASE/ ID NO.	ZL	NO PIER	AVBPR
L/ELEM	SO					SF AVE	HF			NORM DEPTH			ZR		
8627.72	1729.09	7.21	1736.30	1125.5	20.61	6.60	1742.90	.00	8.06		9.00	.00	.00	0	.00
8.86	.02526					.00120	.01			2.86			.00		
8636.58	1729.31	7.59	1736.91	1125.5	19.65	6.00	1742.91	.00	8.06		9.00	.00	.00	0	.00
3.42	.02526					.00110	.00			2.86			.00		
8640.00	1729.40	8.06	1737.46	1125.5	18.73	5.45	1742.91	.00	8.06		9.00	.00	.00	0	.00
NCT STR	.02499					.00919	.04						.00		
8644.00	1729.50	10.21	1739.71	1016.5	15.98	3.97	1743.68	.00	7.77		9.00	.00	.00	0	.00
ANS STR	.19200					.00673	.34						.00		
8694.00	1739.10	4.07	1743.17	1016.5	8.52	1.13	1744.30	.00	3.29		4.00	31.50	.00	2	.75
71.14	.00563					.00464	.33			3.00			.00		
8765.14	1739.50	4.00	1743.50	1016.5	8.52	1.13	1744.63	.00	3.29		4.00	31.50	.00	2	.75
25.48	.00563					.00273	.07			3.00			.00		
8790.62	1739.64	3.81	1743.46	1016.5	8.89	1.23	1744.68	.00	3.29		4.00	31.50	.00	2	.75
21.49	.00563					.00308	.07			3.00			.00		
8812.11	1739.76	3.64	1743.40	1016.5	9.32	1.35	1744.75	.00	3.29		4.00	31.50	.00	2	.75
15.06	.00563					.00349	.05			3.00			.00		
8827.17	1739.85	3.48	1743.33	1016.5	9.73	1.47	1744.80	.00	3.29		4.00	31.50	.00	2	.75
HYDRAULIC JUMP													.00		
8827.17	1739.85	3.11	1742.96	1016.5	10.90	1.85	1744.80	.00	3.29		4.00	31.50	.00	2	.75
15.06	.00563					.00502	.08			3.00			.00		
8842.23	1739.93	3.14	1743.07	1016.5	10.80	1.81	1744.88	.00	3.29		4.00	31.50	.00	2	.75
11.77	.00563					.00464	.05			3.00			.00		
8854.00	1740.00	3.29	1743.29	1016.5	10.29	1.65	1744.94	.00	3.29		4.00	31.50	.00	2	.75

STORM DRAIN ANALYSIS PLUS

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Version 1.20
Serial Number 07010175

Mar 22, 1998 8:44:23

Input file : PIMA4.DAT
Output file: PIMA4.OUT

INPUT FILE LISTING

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T1 PIMA ROAD COLLECTOR CHANNEL  -  DOUBLE BARREL PIPE,  w/ ½ Q IN EACH PIPE
T2 100-YEAR FREQUENCY,   w/ HGL @ SOFFIT ,   WALL EXIT & ENTRANCE
T3 PREPARED BY:     TERRAIN ENGINEERING                  (PIMA4)    3/23/98
   1000.001596.00120      015                1606.00
R  1158.001596.29120      015
R  1430.001596.79120      015                                76.0
   1540.001597.00120      015
   2200.001598.10120      015                                          1
JX 2200.001598.10120 54   015     39.5       1500.85         30.0
R  2620.001598.90120      015                                          1
   3200.001614.05120      015
V                  2      015                                40.0
R  3205.001614.45  2      015
JX 3215.001615.27  3 66   015    203.0       1616.30         30.0
   3220.001615.67  3      015
V                108      015
R  3320.001623.80108      015                                40.0
   3680.001630.70108      015                                          1
   4340.001642.90108      015
JX 4340.001642.90108 60   015     63.0       1645.15         30.0
R  4684.001648.00108      015                                          1
   4860.001654.90108      015
   5344.001660.00108      015                                          1
R  5580.001667.60108      015
R  6004.001674.60108      015                                          1
   6664.001688.00108      015                                          1
   7324.001702.00108      015                                          1
R  7984.001714.20108      015                                          1
   8196.001718.20108      015
   8640.001729.40108      005
JX 8644.001729.50108 66   015    109.0       1631.25         30.00
TS 8694.001739.10  4      015
V                  1      015
   8854.001740.00  1      015
SH                 1      015
```

WATER SURFACE PROFILE - CHANNEL DEFINITION LISTING

ARD CODE	SECT NO	CHN TYPE	NO OF PIERS	AVE PIER WIDTH	HEIGHT 1 DIAMETER	BASE WIDTH	ZL	ZR	INV DROP	Y(1)	Y(2)	Y(3)	Y(4)	Y(5)	Y(6)	Y(7)	Y(8)	Y(9)	Y(10)
D	1	3	2	.75	4.00	31.50	.00	.00	.00										
D	2	3	0	.00	10.00	11.00	.00	.00	.00										
CD	3	3	0	.00	9.00	10.00	.00	.00	.00										
CD	4	3	0	.00	4.00	31.50	.00	.00	.00										
D	54	4			4.50														
D	60	4			5.00														
CD	66	4			5.50														
CD	108	4			9.00														
D	114	4			9.50														
D	120	4			10.00														

WATER SURFACE PROFILE - ELEMENT CARD LISTING

```
ELEMENT NO   1 IS A SYSTEM OUTLET     *         *     *
                U/S DATA   STATION    INVERT  SECT                                W S ELEV
                            1000.00 1596.00  120                                  1606.00

ELEMENT NO   2 IS A REACH             *         *     *
                U/S DATA   STATION    INVERT  SECT              N                          RADIUS  ANGLE  ANG PT  MAN H
                            1158.00 1596.29  120              .015                            .00    .00     .00      0

ELEMENT NO   3 IS A REACH             *         *     *
                U/S DATA   STATION    INVERT  SECT              N                          RADIUS  ANGLE  ANG PT  MAN H
                            1430.00 1596.79  120              .015                            .00  76.00     .00      0

ELEMENT NO   4 IS A REACH             *         *     *
                U/S DATA   STATION    INVERT  SECT              N                          RADIUS  ANGLE  ANG PT  MAN H
                            1540.00 1597.00  120              .015                            .00    .00     .00      0

ELEMENT NO   5 IS A REACH             *         *     *
                U/S DATA   STATION    INVERT  SECT              N                          RADIUS  ANGLE  ANG PT  MAN H
                            2200.00 1598.10  120              .015                            .00    .00     .00      1

ELEMENT NO   6 IS A JUNCTION          *         *     *     *                 *                 *                 *
                U/S DATA   STATION    INVERT  SECT LAT-1 LAT-2   N      Q3       Q4    INVERT-3 INVERT-4  PHI 3   PHI 4
                            2200.00 1598.10  120    54     0   .015    39.5       .0  1500.85      .00  30.00     .00
THE ABOVE ELEMENT CONTAINED AN INVERT ELEV WHICH WAS NOT GREATER THAN THE PREVIOUS INVERT ELEV -WARNING
THE ABOVE ELEMENT CONTAINED AN INVERT ELEV WHICH WAS NOT GREATER THAN THE PREVIOUS INVERT ELEV -WARNING

ELEMENT NO   7 IS A REACH             *         *     *
                U/S DATA   STATION    INVERT  SECT              N                          RADIUS  ANGLE  ANG PT  MAN H
                            2620.00 1598.90  120              .015                            .00    .00     .00      1

ELEMENT NO   8 IS A REACH             *         *     *
                U/S DATA   STATION    INVERT  SECT              N                          RADIUS  ANGLE  ANG PT  MAN H
                            3200.00 1614.05  120              .015                            .00    .00     .00      0

ELEMENT NO   9 IS A  WALL  ENTRANCE                 *
                U/S DATA   STATION    INVERT  SECT             FP
                            3200.00 1614.05    2              .015

ELEMENT NO  10 IS A REACH             *         *     *
                U/S DATA   STATION    INVERT  SECT              N                          RADIUS  ANGLE  ANG PT  MAN H
                            3205.00 1614.45    2              .015                            .00    .00     .00      0

ELEMENT NO  11 IS A JUNCTION          *         *     *     *                 *                 *                 *
                U/S DATA   STATION    INVERT  SECT LAT-1 LAT-2   N      Q3       Q4    INVERT-3 INVERT-4  PHI 3   PHI 4
                            3215.00 1615.27    3    66     0   .015   203.0       .0  1616.30      .00  30.00     .00
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WATER SURFACE PROFILE - ELEMENT CARD LISTING

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ELEMENT NO  12 IS A REACH            *        *    *
                U/S DATA   STATION    INVERT  SECT              N                          RADIUS  ANGLE  ANG PT  MAN H
                            3220.00 1615.67    3              .015                             .00    .00     .00      0

ELEMENT NO  13 IS A  WALL  EXIT                      *
                U/S DATA   STATION    INVERT  SECT
                            3220.00 1615.67  108

ELEMENT NO  14 IS A REACH            *        *    *
                U/S DATA   STATION    INVERT  SECT              N                          RADIUS  ANGLE  ANG PT  MAN H
                            3320.00 1623.80  108              .015                             .00  40.00     .00      0

ELEMENT NO  15 IS A REACH            *        *    *
                U/S DATA   STATION    INVERT  SECT              N                          RADIUS  ANGLE  ANG PT  MAN H
                            3680.00 1630.70  108              .015                             .00    .00     .00      1

ELEMENT NO  16 IS A REACH            *        *    *
                U/S DATA   STATION    INVERT  SECT              N                          RADIUS  ANGLE  ANG PT  MAN H
                            4340.00 1642.90  108              .015                             .00    .00     .00      0

ELEMENT NO  17 IS A JUNCTION         *        *    *    *                 *                 *              *
                U/S DATA   STATION    INVERT  SECT LAT-1 LAT-2   N      Q3       Q4    INVERT-3 INVERT-4  PHI 3   PHI 4
                            4340.00 1642.90  108    60     0   .015    63.0       .0  1645.15      .00  30.00     .00
THE ABOVE ELEMENT CONTAINED AN INVERT ELEV WHICH WAS NOT GREATER THAN THE PREVIOUS INVERT ELEV -WARNING
THE ABOVE ELEMENT CONTAINED AN INVERT ELEV WHICH WAS NOT GREATER THAN THE PREVIOUS INVERT ELEV -WARNING

ELEMENT NO  18 IS A REACH            *        *    *
                U/S DATA   STATION    INVERT  SECT              N                          RADIUS  ANGLE  ANG PT  MAN H
                            4684.00 1648.00  108              .015                             .00    .00     .00      1

ELEMENT NO  19 IS A REACH            *        *    *
                U/S DATA   STATION    INVERT  SECT              N                          RADIUS  ANGLE  ANG PT  MAN H
                            4860.00 1654.90  108              .015                             .00    .00     .00      0

ELEMENT NO  20 IS A REACH            *        *    *
                U/S DATA   STATION    INVERT  SECT              N                          RADIUS  ANGLE  ANG PT  MAN H
                            5344.00 1660.00  108              .015                             .00    .00     .00      1

ELEMENT NO  21 IS A REACH            *        *    *
                U/S DATA   STATION    INVERT  SECT              N                          RADIUS  ANGLE  ANG PT  MAN H
                            5580.00 1667.60  108              .015                             .00    .00     .00      0

ELEMENT NO  22 IS A REACH            *        *    *
                U/S DATA   STATION    INVERT  SECT              N                          RADIUS  ANGLE  ANG PT  MAN H
                            6004.00 1674.60  108              .015                             .00    .00     .00      1

ELEMENT NO  23 IS A REACH            *        *    *
                U/S DATA   STATION    INVERT  SECT              N                          RADIUS  ANGLE  ANG PT  MAN H
                            6664.00 1688.00  108              .015                             .00    .00     .00      1
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WATER SURFACE PROFILE - ELEMENT CARD LISTING

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ELEMENT NO  24 IS A REACH            *        *    *
                U/S DATA   STATION    INVERT  SECT              N                                RADIUS  ANGLE  ANG PT  MAN H
                            7324.00 1702.00  108              .015                                  .00    .00     .00      1

ELEMENT NO  25 IS A REACH            *        *    *
                U/S DATA   STATION    INVERT  SECT              N                                RADIUS  ANGLE  ANG PT  MAN H
                            7984.00 1714.20  108              .015                                  .00    .00     .00      1

ELEMENT NO  26 IS A REACH            *        *    *
                U/S DATA   STATION    INVERT  SECT              N                                RADIUS  ANGLE  ANG PT  MAN H
                            8196.00 1718.20  108              .015                                  .00    .00     .00      0

ELEMENT NO  27 IS A REACH            *        *    *
                U/S DATA   STATION    INVERT  SECT              N                                RADIUS  ANGLE  ANG PT  MAN H
                            8640.00 1729.40  108              .005                                  .00    .00     .00      0

ELEMENT NO  28 IS A JUNCTION         *        *    *    *                *                 *              *
                U/S DATA   STATION    INVERT  SECT LAT-1 LAT-2   N      Q3       Q4    INVERT-3 INVERT-4  PHI 3   PHI 4
                            8644.00 1729.50  108    66     0   .015    109.0       .0  1631.25      .00  30.00     .00

ELEMENT NO  29 IS A TRANSITION       *        *    *
                U/S DATA   STATION    INVERT  SECT              N
                            8694.00 1739.10    4              .015

ELEMENT NO  30 IS A  WALL  EXIT                   *
                U/S DATA   STATION    INVERT  SECT
                            8694.00 1739.10    1

ELEMENT NO  31 IS A REACH            *        *    *
                U/S DATA   STATION    INVERT  SECT              N                                RADIUS  ANGLE  ANG PT  MAN H
                            8854.00 1740.00    1              .015                                  .00    .00     .00      0

ELEMENT NO  32 IS A SYSTEM HEADWORKS                  *                    *
                U/S DATA   STATION    INVERT  SECT                                     W S ELEV
                            8854.00 1740.00    1                                          .00
NO EDIT ERRORS ENCOUNTERED-COMPUTATION IS NOW BEGINNING

** WARNING NO. 2 ** - WATER SURFACE ELEVATION GIVEN IS LESS THAN OR EQUALS INVERT ELEVATION IN HDWKDS, W.S.ELEV = INV + DC
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WATER SURFACE PROFILE LISTING

PIMA ROAD COLLECTOR CHANNEL - DOUBLE BARREL PIPE, w/ ½ Q IN EACH PIPE
100-YEAR FREQUENCY, w/ HGL @ SOFFIT , WALL EXIT & ENTRANCE
PREPARED BY: TERRAIN ENGINEERING (PIMA4) 3/23/98

STATION / L/ELEM	INVERT ELEV / SO	DEPTH OF FLOW	W.S. ELEV	Q	VEL	VEL HEAD / SF AVE	ENERGY GRD.EL. / HF	SUPER ELEV	CRITICAL DEPTH / NORM DEPTH	HGT/ DIA	BASE/ ID NO.	ZL / ZR	NO PIER	AVBPR
1000.00	1596.00	10.00	1606.00	1431.0	18.22	5.16	1611.16	.00	8.88	10.00	.00	.00	0	.00
158.00	.00184					.00997	1.58		10.00			.00		
1158.00	1596.29	11.29	1607.58	1431.0	18.22	5.16	1612.73	.00	8.88	10.00	.00	.00	0	.00
272.00	.00184					.00997	2.71		10.00			.00		
1430.00	1596.79	14.44	1611.23	1431.0	18.22	5.16	1616.39	.00	8.88	10.00	.00	.00	0	.00
110.00	.00191					.00997	1.10		10.00			.00		
1540.00	1597.00	15.33	1612.33	1431.0	18.22	5.16	1617.49	.00	8.88	10.00	.00	.00	0	.00
660.00	.00167					.00997	6.58		10.00			.00		
2200.00	1598.10	21.07	1619.17	1431.0	18.22	5.16	1624.33	.00	8.88	10.00	.00	.00	0	.00
NCT STR	.00000					.00970	.00					.00		
2200.00	1598.10	21.60	1619.70	1391.5	17.72	4.88	1624.58	.00	8.80	10.00	.00	.00	0	.00
420.00	.00190					.00943	3.96		10.00			.00		
2620.00	1598.90	25.00	1623.90	1391.5	17.72	4.88	1628.78	.00	8.80	10.00	.00	.00	0	.00
580.00	.02612					.00943	5.47		5.59			.00		
3200.00	1614.05	15.32	1629.37	1391.5	17.72	4.88	1634.25	.00	8.80	10.00	.00	.00	0	.00
WALL ENTRANCE												.00		
3200.00	1614.05	17.73	1631.78	1391.5	12.68	2.50	1634.28	.00	7.92	10.00	11.00	.00	0	.00
5.00	.07998					.00455	.02		2.93			.00		
3205.00	1614.45	17.36	1631.81	1391.5	12.68	2.50	1634.30	.00	7.92	10.00	11.00	.00	0	.00
JUNCT STR	.08201					.00512	.05					.00		
3215.00	1615.27	16.71	1631.98	1188.5	13.24	2.73	1634.71	.00	7.60	9.00	10.00	.00	0	.00
5.00	.08000					.00568	.03		2.85			.00		

WATER SURFACE PROFILE LISTING

PIMA ROAD COLLECTOR CHANNEL - DOUBLE BARREL PIPE, w/ ½ Q IN EACH PIPE

100-YEAR FREQUENCY, w/ HGL @ SOFFIT , WALL EXIT & ENTRANCE

PREPARED BY: TERRAIN ENGINEERING (PIMA4) 3/23/98

STATION	INVERT ELEV	DEPTH OF FLOW	W.S. ELEV	Q	VEL	VEL HEAD	ENERGY GRD.EL.	SUPER ELEV	CRITICAL DEPTH		HGT/ DIA	BASE/ ID NO.	ZL	NO PIER	AVBPR
L/ELEM	SO					SF AVE	HF			NORM DEPTH			ZR		
3220.00	1615.67	16.34	1632.01	1188.5	13.24	2.73	1634.74	.00	7.60		9.00	10.00	.00	0	.00
WALL EXIT													.00		
3220.00	1615.67	16.34	1632.01	1188.5	18.68	5.42	1637.43	.00	8.20		9.00	.00	.00	0	.00
75.87	.08130					.01206	.92			3.88			.00		
3295.87	1621.84	11.64	1633.47	1188.5	18.68	5.42	1638.90	.00	8.20		9.00	.00	.00	0	.00
DRAULIC JUMP													.00		
3295.87	1621.84	5.67	1627.51	1188.5	28.16	12.32	1639.83	.00	8.20		9.00	.00	.00	0	.00
11.20	.08130					.02213	.25			3.88			.00		
3307.07	1622.75	5.84	1628.59	1188.5	27.19	11.49	1640.08	.00	8.20		9.00	.00	.00	0	.00
12.93	.08130					.01998	.26			3.88			.00		
3320.00	1623.80	6.09	1629.89	1188.5	25.92	10.44	1640.34	.00	8.20		9.00	.00	.00	0	.00
360.00	.01917					.01840	6.62			6.05			.00		
680.00	1630.70	6.20	1636.90	1188.5	25.45	10.06	1646.96	.00	8.20		9.00	.00	.00	0	.00
.00	.01917					.01798	.00			6.05			.00		
680.00	1630.70	6.20	1636.90	1188.5	25.45	10.06	1646.96	.00	8.20		9.00	.00	.00	0	.00
167.37	.01849					.01781	2.98			6.13			.00		
847.37	1633.79	6.24	1640.03	1188.5	25.25	9.91	1649.94	.00	8.20		9.00	.00	.00	0	.00
347.70	.01849					.01670	5.81			6.13			.00		
195.06	1640.22	6.52	1646.74	1188.5	24.07	9.01	1655.75	.00	8.20		9.00	.00	.00	0	.00
144.94	.01849					.01495	2.17			6.13			.00		
340.00	1642.90	6.83	1649.73	1188.5	22.95	8.19	1657.92	.00	8.20		9.00	.00	.00	0	.00
JUNCT STR	.00000					.01614	.00						.00		

WATER SURFACE PROFILE LISTING

PIMA ROAD COLLECTOR CHANNEL - DOUBLE BARREL PIPE, w/ ½ Q IN EACH PIPE
100-YEAR FREQUENCY, w/ HGL @ SOFFIT , WALL EXIT & ENTRANCE
PREPARED BY: TERRAIN ENGINEERING (PIMA4) 3/23/98

STATION	INVERT ELEV	DEPTH OF FLOW	W.S. ELEV	Q	VEL	VEL HEAD	ENERGY GRD.EL.	SUPER ELEV	CRITICAL DEPTH		HGT/ DIA	BASE/ ID NO.	ZL	NO PIER	AVBPR
L/ELEM	SO					SF AVE	HF			NORM DEPTH			ZR		
4340.00	1642.90	5.94	1648.84	1125.5	25.29	9.94	1658.77	.00	8.06		9.00	.00	.00	0	.00
JNCT STR	.00000					.01814	.00						.00		
4340.00	1642.90	5.94	1648.84	1125.5	25.29	9.94	1658.77	.00	8.06		9.00	.00	.00	0	.00
85.60	.01483					.01864	1.60			6.40			.00		
4425.60	1644.17	5.82	1649.99	1125.5	25.84	10.38	1660.37	.00	8.06		9.00	.00	.00	0	.00
145.23	.01483					.02036	2.96			6.40			.00		
4570.83	1646.32	5.59	1651.91	1125.5	27.10	11.42	1663.33	.00	8.06		9.00	.00	.00	0	.00
113.17	.01483					.02297	2.60			6.40			.00		
4684.00	1648.00	5.37	1653.37	1125.5	28.43	12.56	1665.93	.00	8.06		9.00	.00	.00	0	.00
.00	.01483					.02437	.00			6.40			.00		
4684.00	1648.00	5.37	1653.37	1125.5	28.43	12.56	1665.93	.00	8.06		9.00	.00	.00	0	.00
52.21	.03920					.02310	1.21			4.63			.00		
4736.21	1650.05	5.57	1655.62	1125.5	27.23	11.52	1667.13	.00	8.06		9.00	.00	.00	0	.00
43.80	.03920					.02059	.90			4.63			.00		
4780.01	1651.76	5.80	1657.57	1125.5	25.96	10.47	1668.04	.00	8.06		9.00	.00	.00	0	.00
33.65	.03920					.01828	.62			4.63			.00		
4813.66	1653.08	6.05	1659.13	1125.5	24.75	9.52	1668.65	.00	8.06		9.00	.00	.00	0	.00
26.13	.03920					.01627	.43			4.63			.00		
4839.79	1654.11	6.32	1660.42	1125.5	23.60	8.65	1669.08	.00	8.06		9.00	.00	.00	0	.00
20.21	.03920					.01452	.29			4.63			.00		
4860.00	1654.90	6.60	1661.50	1125.5	22.50	7.87	1669.37	.00	8.06		9.00	.00	.00	0	.00
17.33	.01054					.01380	.24			7.49			.00		

WATER SURFACE PROFILE LISTING

PIMA ROAD COLLECTOR CHANNEL - DOUBLE BARREL PIPE, w/ ½ Q IN EACH PIPE
100-YEAR FREQUENCY, w/ HGL @ SOFFIT , WALL EXIT & ENTRANCE
PREPARED BY: TERRAIN ENGINEERING (PIMA4) 3/23/98

STATION	INVERT ELEV	DEPTH OF FLOW	W.S. ELEV	Q	VEL	VEL HEAD	ENERGY GRD.EL.	SUPER ELEV	CRITICAL DEPTH		HGT/ DIA	BASE/ ID NO.	ZL	NO PIER	AVBPR
L/ELEM	SO					SF AVE	HF			NORM DEPTH			ZR		
4877.33	1655.08	6.57	1661.65	1125.5	22.64	7.96	1669.61	.00	8.06		9.00	.00	.00	0	.00
122.02	.01054					.01473	1.80			7.49			.00		
4999.35	1656.37	6.28	1662.65	1125.5	23.74	8.76	1671.41	.00	8.06		9.00	.00	.00	0	.00
102.63	.01054					.01651	1.69			7.49			.00		
5101.99	1657.45	6.02	1663.47	1125.5	24.90	9.64	1673.10	.00	8.06		9.00	.00	.00	0	.00
89.44	.01054					.01856	1.66			7.49			.00		
5191.43	1658.39	5.77	1664.16	1125.5	26.12	10.60	1674.76	.00	8.06		9.00	.00	.00	0	.00
79.91	.01054					.02091	1.67			7.49			.00		
5271.34	1659.23	5.54	1664.77	1125.5	27.39	11.66	1676.43	.00	8.06		9.00	.00	.00	0	.00
72.66	.01054					.02360	1.71			7.49			.00		
5344.00	1660.00	5.32	1665.32	1125.5	28.73	12.82	1678.15	.00	8.06		9.00	.00	.00	0	.00
109.54	.03220					.02362	2.59			4.92			.00		
5453.54	1663.53	5.54	1669.07	1125.5	27.40	11.67	1680.74	.00	8.06		9.00	.00	.00	0	.00
73.75	.03220					.02094	1.54			4.92			.00		
5527.29	1665.90	5.77	1671.67	1125.5	26.13	10.61	1682.28	.00	8.06		9.00	.00	.00	0	.00
52.71	.03220					.01858	.98			4.92			.00		
5580.00	1667.60	6.01	1673.61	1125.5	24.91	9.64	1683.26	.00	8.06		9.00	.00	.00	0	.00
142.95	.01651					.01776	2.54			6.14			.00		
5722.95	1669.96	5.95	1675.91	1125.5	25.23	9.89	1685.80	.00	8.06		9.00	.00	.00	0	.00
281.05	.01651					.01917	5.39			6.14			.00		
6004.00	1674.60	5.71	1680.31	1125.5	26.46	10.88	1691.19	.00	8.06		9.00	.00	.00	0	.00
6.50	.02030					.02031	.13			5.71			.00		

WATER SURFACE PROFILE LISTING
PIMA ROAD COLLECTOR CHANNEL - DOUBLE BARREL PIPE, w/ ½ Q IN EACH PIPE
100-YEAR FREQUENCY, w/ HGL @ SOFFIT , WALL EXIT & ENTRANCE
PREPARED BY: TERRAIN ENGINEERING (PIMA4) 3/23/98

STATION / L/ELEM	INVERT ELEV / SO	DEPTH OF FLOW	W.S. ELEV	Q	VEL	VEL HEAD / SF AVE	ENERGY GRD.EL. / HF	SUPER ELEV	CRITICAL DEPTH / NORM DEPTH	HGT/ DIA	BASE/ ID NO.	ZL / ZR	NO PIER	AVBPR
6010.50	1674.73	5.71	1680.44	1125.5	26.46	10.88	1691.32	.00	8.06	9.00	.00	.00	0	.00
653.50	.02030					.02076	13.57		5.71			.00		
6664.00	1688.00	5.62	1693.62	1125.5	26.92	11.26	1704.88	.00	8.06	9.00	.00	.00	0	.00
660.00	.02121					.02061	13.60		5.62			.00		
7324.00	1702.00	5.74	1707.74	1125.5	26.30	10.75	1718.49	.00	8.06	9.00	.00	.00	0	.00
.00	.02121					.02001	.00		5.62			.00		
7324.00	1702.00	5.74	1707.74	1125.5	26.30	10.75	1718.49	.00	8.06	9.00	.00	.00	0	.00
168.67	.01849					.02053	3.46		5.90			.00		
7492.67	1705.12	5.64	1710.75	1125.5	26.84	11.20	1721.95	.00	8.06	9.00	.00	.00	0	.00
228.19	.01849					.02241	5.11		5.90			.00		
7720.86	1709.34	5.41	1714.75	1125.5	28.15	12.32	1727.07	.00	8.06	9.00	.00	.00	0	.00
149.41	.01849					.02532	3.78		5.90			.00		
7870.27	1712.10	5.20	1717.30	1125.5	29.53	13.55	1730.85	.00	8.06	9.00	.00	.00	0	.00
113.73	.01849					.02865	3.26		5.90			.00		
7984.00	1714.20	5.01	1719.21	1125.5	30.97	14.90	1734.11	.00	8.06	9.00	.00	.00	0	.00
47.18	.01887					.03133	1.48		5.85			.00		
8031.18	1715.09	4.92	1720.01	1125.5	31.66	15.58	1735.59	.00	8.06	9.00	.00	.00	0	.00
88.46	.01887					.03440	3.04		5.85			.00		
8119.64	1716.76	4.73	1721.49	1125.5	33.21	17.14	1738.63	.00	8.06	9.00	.00	.00	0	.00
76.36	.01887					.03902	2.98		5.85			.00		
8196.00	1718.20	4.56	1722.76	1125.5	34.83	18.85	1741.61	.00	8.06	9.00	.00	.00	0	.00
-.00	.01887					.02305	.00		5.85			.00		

WATER SURFACE PROFILE LISTING

PIMA ROAD COLLECTOR CHANNEL - DOUBLE BARREL PIPE, w/ ½ Q IN EACH PIPE

100-YEAR FREQUENCY, w/ HGL @ SOFFIT , WALL EXIT & ENTRANCE

PREPARED BY: TERRAIN ENGINEERING (PIMA4) 3/23/98

STATION	INVERT ELEV	DEPTH OF FLOW	W.S. ELEV	Q	VEL	VEL HEAD	ENERGY GRD.EL.	SUPER ELEV	CRITICAL DEPTH		HGT/ DIA	BASE/ ID NO.	ZL	NO PIER	AVBPR
L/ELEM	SO					SF AVE	HF			NORM DEPTH			ZR		
8196.00	1718.20	4.56	1722.76	1125.5	34.83	18.85	1741.61	.00	8.06		9.00	.00	.00	0	.00
.89	.02523					.00461	.00			2.86			.00		
8196.89	1718.22	4.56	1722.78	1125.5	34.81	18.83	1741.61	.00	8.06		9.00	.00	.00	0	.00
73.56	.02523					.00433	.32			2.86			.00		
8270.46	1720.08	4.73	1724.81	1125.5	33.19	17.12	1741.93	.00	8.06		9.00	.00	.00	0	.00
64.11	.02523					.00382	.24			2.86			.00		
8334.57	1721.70	4.92	1726.61	1125.5	31.65	15.56	1742.18	.00	8.06		9.00	.00	.00	0	.00
55.82	.02523					.00337	.19			2.86			.00		
8390.38	1723.10	5.11	1728.22	1125.5	30.17	14.15	1742.36	.00	8.06		9.00	.00	.00	0	.00
48.65	.02523					.00298	.14			2.86			.00		
8439.03	1724.33	5.32	1729.65	1125.5	28.77	12.86	1742.51	.00	8.06		9.00	.00	.00	0	.00
42.15	.02523					.00263	.11			2.86			.00		
8481.18	1725.39	5.53	1730.93	1125.5	27.43	11.69	1742.62	.00	8.06		9.00	.00	.00	0	.00
36.39	.02523					.00233	.08			2.86			.00		
8517.57	1726.31	5.76	1732.07	1125.5	26.15	10.63	1742.71	.00	8.06		9.00	.00	.00	0	.00
31.11	.02523					.00207	.06			2.86			.00		
8548.69	1727.10	6.01	1733.11	1125.5	24.94	9.66	1742.77	.00	8.06		9.00	.00	.00	0	.00
26.33	.02523					.00184	.05			2.86			.00		
8575.01	1727.76	6.27	1734.03	1125.5	23.78	8.79	1742.82	.00	8.06		9.00	.00	.00	0	.00
21.87	.02523					.00164	.04			2.86			.00		
8596.88	1728.31	6.56	1734.87	1125.5	22.67	7.99	1742.85	.00	8.06		9.00	.00	.00	0	.00
17.52	.02523					.00147	.03			2.86			.00		

WATER SURFACE PROFILE LISTING

PIMA ROAD COLLECTOR CHANNEL - DOUBLE BARREL PIPE, w/ ½ Q IN EACH PIPE
100-YEAR FREQUENCY, w/ HGL @ SOFFIT , WALL EXIT & ENTRANCE
PREPARED BY: TERRAIN ENGINEERING (PIMA4) 3/23/98

STATION	INVERT ELEV	DEPTH OF FLOW	W.S. ELEV	Q	VEL	VEL HEAD	ENERGY GRD.EL.	SUPER ELEV	CRITICAL DEPTH		HGT/ DIA	BASE/ ID NO.	ZL	NO PIER	AVBPR
L/ELEM	SO					SF AVE	HF			NORM DEPTH			ZR		
8614.40	1728.75	6.87	1735.62	1125.5	21.62	7.26	1742.88	.00	8.06		9.00	.00	.00	0	.00
13.31	.02523					.00132	.02			2.86			.00		
8627.71	1729.09	7.21	1736.30	1125.5	20.61	6.60	1742.90	.00	8.06		9.00	.00	.00	0	.00
8.87	.02523					.00120	.01			2.86			.00		
8636.57	1729.31	7.59	1736.91	1125.5	19.65	6.00	1742.91	.00	8.06		9.00	.00	.00	0	.00
3.43	.02523					.00110	.00			2.86			.00		
8640.00	1729.40	8.06	1737.46	1125.5	18.73	5.45	1742.91	.00	8.06		9.00	.00	.00	0	.00
NCT STR	.02499					.00919	.04						.00		
8644.00	1729.50	10.21	1739.71	1016.5	15.98	3.97	1743.68	.00	7.77		9.00	.00	.00	0	.00
ANS STR	.19200					.00597	.30						.00		
8694.00	1739.10	4.16	1743.26	1016.5	8.08	1.02	1744.27	.00	3.19		4.00	31.50	.00	0	.00
WALL EXIT													.00		
8694.00	1739.10	4.16	1743.26	1016.5	8.52	1.13	1744.39	.00	3.29		4.00	31.50	.00	2	.75
159.42	.00563					.00464	.74			3.00			.00		
8853.42	1740.00	4.00	1744.00	1016.5	8.52	1.13	1745.13	.00	3.29		4.00	31.50	.00	2	.75
.58	.00563					.00255	.00			3.00			.00		
8854.00	1740.00	4.00	1744.00	1016.5	8.48	1.12	1745.11	.00	3.29		4.00	31.50	.00	2	.75

COMPUTER PROGRAM F0515P

W S P G

Water Surface and Pressure Gradient

Hydraulic Analysis System

USER MANUAL

April 1979

Los Angeles County Flood Control District
A. E. Bruington, Chief Engineer

2250 Alcazar Street, Los Angeles
Telephone: (213) 226-4111

P.O. Box 2418 Terminal Annex
Los Angeles, CA 90054

1.1 Introduction

This program is a hydraulic analysis system developed by the Design Systems and Standards Group of the Design Division and the Data Processing Section of the Business and Fiscal Division of the Los Angeles County Flood Control District.

2.1 Purpose

The program computes and plots uniform and nonuniform steady flow water surface profiles and pressure gradients in open channels or closed conduits with irregular or regular sections. The flow in a system may alternate between super critical, subcritical or pressure flow in any sequence. The program will also analyze natural river channels although the principle use of the program is intended for determining profiles in improved flood control systems.

3.1 General Program Description

3.2 Basic Theory

The computational procedure is based on solving Bernoulli's equation for the total energy at each section and Manning's formula for friction loss between the sections in a reach. The open channel flow procedure utilizes the standard step method. Confluences and bridge piers are analyzed using pressure and momemtum theory.

The program uses basic mathematical and hydraulic principles to calculate all such data as cross sectional area, wetted perimeter, normal depth, critical depth, pressure, and momentum.

3.3 Computational Procedure

3.3.1 Input Preparation

The channel or conduit system is initially subdivided into the following elements: system outlet, reach, transition, confluence (junction), bridge exit, bridge entrance, wall entrance (sudden contraction), wall exit (sudden expansion), and system headworks. Each element is internally assigned a number. The input data must consist of a minimum of three elements (system outlet, system headwork and any other element) and is limited to a maximum of 200 elements. A greater number of elements will require a breakup into two or more systems.

3.3.2 Flow Rates

The starting flow rate (Q) at the upstream terminus of a system is specified on a "Q" card. The flow rate (Q) is increased at the desired locations by specifying lateral inflow rates on the "JX" cards. The flow rate can be reduced by using a negative lateral Q, this reduction is intended to account for channel storage. If it is used in cases where the channel or conduit branches it should be understood no loss is computed.

3.3.3 Multiple Profiles

To obtain additional watersurface or pressure gradient profiles for different flow rates in the system, additional Q cards may be supplied. The only limitation on the number of profiles that may be run at one time is the limit on the program execution time which is set by the computer center.

3.3.4 Manning's "n"

The program uses the Manning formula for the friction loss in all types of conduits or natural channels. The program can only take one "n" value per element, however, the "n" value can change at subsequent elements. If a section has a lining composed of different roughness coefficients a composite "n" based on anticipated depth of flow should be hand computed. If an "n" value is not specified with the input data, the program uses a value of .014.

3.3.5 Water Surface Controls

Water surface controls at the downstream terminus (System Outlet S.O.) or the upstream terminus (System Headworks S.H.) are optional input values. If water-surface controls are not given the program will use critical depth controls.

3.3.6 Critical and Normal Depths

Critical depth is computed for every section for the given Q utilizing the "Specific Energy Equation".

Normal depth is computed in every reach element on a positive slope for the specified Q.

The velocity head (H_V) is computed using the mean velocity of the section. This may not be accurate in the case of a complex section such as one with shallow flow in the horizontal overbank area where velocity distribution is not uniform. If the program is to be used in this situation the user should be aware that some error may be introduced in the results. A check on the magnitude of the error can be made by the user utilizing the parabolic method to determine specific energy (see Appendix).

3.3.7 Watersurface Stages

The lower stage w.s. profile begins at the system headworks and ends at the system outlet. The computation will proceed downstream in every consecutive element as long as energy is available to maintain flow in the supercritical stage. When energy becomes expended at any point in an element, the lower stage profile will be discontinued from that point to the downstream end of that element. Then computation will resume in the next element with a critical depth control until the system outlet is analyzed.

The upper stage w.s. profile, begins at the system outlet, and ends at the headworks. Computation proceeds upstream in every element as long as the water surface at the downstream end of any two adjacent points can support the moving mass of water to flow at the critical or subcritical depth. Otherwise, computation will be discontinued from the downstream point to the upstream end of that element. Then computation will resume at the downstream end of the next element with critical depth control, provided no depth less than critical depth has been computed at that point on the lower stage profile. Then computation will proceed upstream until the system headworks is analyzed. Note that if the computed depth of flow in any open section exceeds the given section height the program will assume an additional 10-feet of vertical wall except for Channel Type 1 (see Figure 6-1) where the side slopes are extended outward until the 10-feet vertical height is reached.

The jump routine begins at the system outlet and ends at the headworks. It searches the lower stage and the upper stage profiles for points of equal energy. If a jump is encountered, it will be approximately located; and data on either the upper stage or lower stage not consistent with the greater energy theory will be deleted from every element. The final profile will be a composite of upper stage and lower stage with hydraulic jumps in between.

12.4 COMPUTATIONAL PROCEDURES

Assumptions are: Steady one dimentional flow and incompressible fluids.

12.4.1 BASIC EQUATIONS OF STEADY FLOW

a) Equation of Continuity

$$A1.V1 = A2.V2 = Q$$

b) Manning's Formula (friction slope)

$$Sf = \left\{ Q\,n/[1.486\,A\,(RH)^{\frac{2}{3}}] \right\}^2$$

c) Bernoulli's Equation (open flow)

$$D2 + HV2 + \Delta L\ Sfav = D1 + HV1 + \Delta L\ So \quad \text{where } HV = V^2/2g$$

d) Bernoulli's Equation (pressure flow)

$$D2 + HV2 + \Delta L\ Sfav + Hm = D1 + HV1 + \Delta L\ So$$

where Hm is miscel.losses.

e) Angle Point Loss

$$Hapt = 0.0033\ \Theta\ HV$$

Where Θ is deflection angle in degrees. The District recommends not to exceed 6°.

f) Bend Loss

$$HB = 0.2\ HV \sqrt{\Delta/90}$$

where Δ is central angle of bend in degrees.

g) Manhole Loss

Hmh = 0.05 HV (No. MN) where No. MH is number of manholes in a reach

h) Specific Energy

$E = D + HV$

i) Pressure - Momentum

$P2 + M2 = P1 + M1 = F$

where $M = (Q)^2 / (Ag)$

j) Critical Depth Dc

Dc is the depth of flow at minimun energy, to find Dc by parabolic method see References 12.6.4 otherwise iterate for Dc in the specific energy equat.

$Ec = f(Dc) = Dc + HVC$

k) Normal Depth Dn

Dn is the depth of uniform flow and is found by iteration from Manning's formula

$A(RH)^{2/3} = f(Dn) = [Q\ n] / [1.486\ So^{1/2}]$

12.4.2 REACH ANALYSIS

a) Open Flow

Intermediate points are computed on the W.S. profile in a reach using the standard step method. The difference in velocity head between two adjacent points is held to a maximum of ten per cent.

$$\Delta L = (E2 - E1) / (So - Sfav)$$

b) Pressure Flow

$$EGL\ 1 = EGL\ 2 + Hf + Hm$$

$$D1 = EGL\ 1 - HV1 - INV.\ 1$$

If W.S. profile rises to the soffit of a conduit before the end of the reach or if the H.G.L. breaks seal before the end of the reach, minor losses are adjusted to reflect only the portion of the reach under pressure.

Super Elevation (S.E.)

Super elevation is computed in curving channels as follows:

CHAN. TYPE 1: (Trap. Sect.)

Subcritical flow: $S.E. = 1.15\ [HV/r]\ [b + D\ (ZL + ZR)]$

Supercritical flow: $S.E. = 2.6\ [HV/r]\ [b + D\ (ZL + ZR)]$

CHAN. TYPE 2: (Rect. Sect.)

Subcritical flow: $S.E. = HV\ b/r$

Supercritical flow: $S.E. = 2\ HV\ b/r$

12.4.3 TRANSITION ANALYSIS

If V2 is greater than V1 then

$Ht = 0.1\ [HV2 - HV1]$

otherwise

$Ht = 0.2\ [HV1 - HV2]$

12.4.4 JUNCTION ANALYSIS

$\triangle Y = [(Q2.V2) - (Q1.V1) - (Q3.V3.COSO3)\ (1/g)\ (1/A\ ave)] + \triangle L\ Sf\ av$

where $A\ ave = [(A1 + A2)/2]$

and $\triangle Y = D1 + \triangle H - D2$

$HJ = \triangle Y + HV1 - HV2$

12.4.6 WALL ENTRANCE ANALYSIS (Sudden Contraction)

Lower Stage Profile (U/S Control)

Find depth at the D/S end by iteration in the equation.

M2 + P2 = M1 [(A1-A1WALL) / A1] + P1 - P1 walls

where A1 wall is the area of the obstructed part of A1. And P1 wall is the pressure on the obstructed part of A1

Upper Stage Profile (D/S Control)

If the control depth is less than the conduit height find the depth at the U/S end from

M2 + P2 = M1 [(A1-A1WALL) / A1] + P1 - P1 wall

otherwise find D1 by iteration from the following equation:

D2 + HV2 + Kc ABS [HV2 - HV1] = D1 + HV1

where Kc ABS [HV2 - HV1] is the head loss at WE.

Kc = 0.5 unless given otherwise

ABS = the absolute value

12.4.7 WALL EXIT (Sudden Expansion)

Energy loss in a wall exit = 1.0 ABS [HV2 - HV1]

In WX find D1 or D2 by iteration in the following

D2 + HV2 + 1.0 ABS [HV2 - HV1] = D1 + HV1

CONCLUSIONS AND LIMITATIONS

CONCLUSIONS AND LIMITATIONS

This report is based on design and construction experience with cast-in-place earth reinforced concrete pipe, on a detailed review of the referenced Agra Earth and Environmental, Inc. Geotechnical report and on a hydraulic review using "Water Surface Pressure Gradient" program developed by Los Angeles County Department of Public Works.

From this information professional engineering judgment as to the suitability of the project soils have been made and pipe design criteria for soil weight and shear strength have been determined. These data along with a selection of an appropriate concrete strength (f'c) are utilized in the employed structural analysis program, to make the recommendation that Cast-in-Place Earth Reinforced Concrete Pipe is a suitable alternative to reinforced concrete pipe (RCP.)

If during design or construction, differing site conditions are encountered, the contractor or owner representative shall notify this firm immediately so that alternate written recommendations can be made.

The hydraulic review has been done to current concrete pipe design standards. The analysis used allows for the recommendations regarding pipe diameters and for the recommendation that Cast-in Place Concrete Pipe is a suitable alternative to RCP.

This report is applicable to City of Scottsdale Desert Greenbelt, Pima Road Three Basins (PR3B) Project as described herein and shall not be utilized for design or construction on any other site.

PUBLISHED PAPERS ON CAST-IN-PLACE CONCRETE PIPE PERFORMANCE

TRANSPORTATION RESEARCH

RECORD

No. 1415

Soils, Geology, and Foundations

Field Performance of Structures and Nondestructive Evaluation of Subsurface Infrastructure

A peer-reviewed publication of the Transportation Research Board

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL

NATIONAL ACADEMY PRESS
WASHINGTON, D.C. 1993

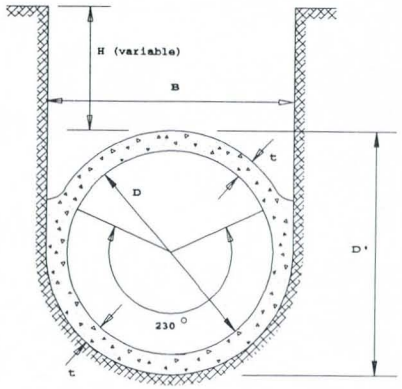

FIGURE 1 Typical cross section of cast-in-place concrete pipe [610–3048 mm (24–120 in.)].

(1- to 3-in.) concrete of modest strength with a minimum 28-day strength of 20.7 MPa (3,000 psi) is placed, tamped, and vibrated to achieve full consolidation. A polyethylene blanket is often used for accelerated curing. Under typical conditions, the production rate ranges from 30 m (100 ft) to 7 m (23 ft) per hour depending on the size, 610-mm diameter to 3048-mm diameter, of the pipe.

After 6 hr, the top forms may be removed. When the concrete achieves a strength of 17.2 MPa (2,500 psi), usually in 2 to 3 days, trench backfilling may begin. Circumferential shrinkage cracks, which are best understood to be joints in the continuously cast pipe, will appear every 7.6 m (25 ft) to 15.2 m (50 ft), or more, depending on curing conditions, the quality of the concrete, and trench moisture conditions. The cracks have no structural significance and need only to be grouted to prevent infiltration, if such is a consideration.

DESIGN CONSIDERATIONS

The following ACI (*1*) engineering design procedure yields a statement of the stress in the pipe wall.

Marston earth loads for the trench conditions are used to define vertical dead loads. Appropriate AASHTO highway loads, FAA aircraft loads, and Cooper rail loads define the live loads. Compensating lateral loads (see section on Structural Performance of Concrete Pipe) are taken conservatively as Rankine active pressures, a significant underestimate of the passive pressures known to be working when the stiff lateral walls are engaged by the pipe. The pipe dead load, the weight of the water in the pipe, and hydrostatic heads may be included as required.

Moments and thrusts may be computed using coefficients developed by Paris (*3*) or Roark compiled by Young (*4*). Stresses at critical points of tension (at crown, invert, and springline) are calculated in appropriate units from the following interaction formula:

$$f = (6M/t^2) - (T/t)$$

TABLE 1 Dimensions of Cast-in-Place Concrete Pipe

NOMINAL DIAMETER (Interior)		OUTSIDE DIAMETER (Depth)		WIDTH OF PIPE/TRENCH (Nominal)		WALL THICKNESS (Minimum)	
D		D'		B		t	
mm	inches	mm	inches	mm	inches	mm	inches
610	24	762	30	787	31	76	3.0
686	27	838	33	864	34	76	3.0
762	30	914	36	940	37	76	3.0
914	36	1092	43	1118	44	89	3.5
1067	42	1270	50	1295	51	102	4.0
1219	48	1473	58	1499	59	127	5.0
1372	54	1651	65	1676	66	140	5.5
1524	60	1829	72	1854	73	152	6.0
1676	66	2007	79	2032	80	165	6.5
1829	72	2184	86	2210	87	178	7.0
1981	78	2362	93	2388	94	191	7.5
2134	84	2540	100	2565	101	203	8.0
2438	96	2896	114	2921	115	229	9.0
2743	108	3277	129	3302	130	267	10.5
3048	120	3658	144	3683	145	305	12.0

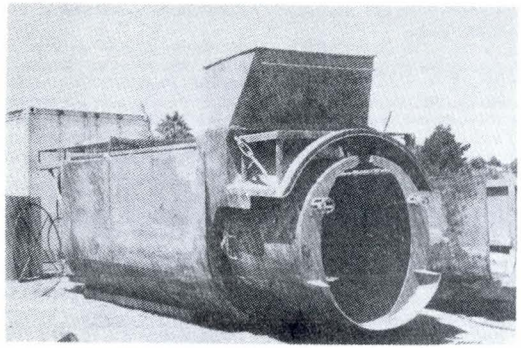

FIGURE 2 Pipe casting machine.

where

M = moment per unit length of pipe (N·m/m),
t = thickness (mm),
T = circumferential thrust per unit length of pipe (m), and
f = stress (MPa).

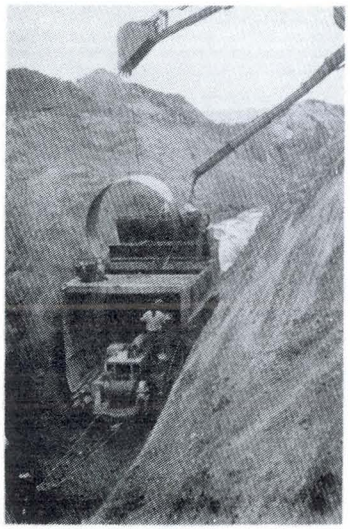

FIGURE 3 Pipe case in prepared trench.

Alternatively, a stress analysis may be obtained from finite element studies, such as CANDE, wherein a round pipe of constant wall thickness may be used to approximate the configuration shown in Figure 1.

FIELD PERFORMANCE STUDIES

The following is a list of studies known to the authors that illustrate the structural performance of CIPCP.

1. Gravity load test performed by Fortier (*5*), 1954, Fresno, California; pipe diameter = 762 mm (30 in.); soil type, sandy loam/silica with cemented hardpan; f'_c = 15.2 MPa (2,200 psi); loading with modified ASTM sand box; visual observation for distress.

Test and results: A 4-ft section was loaded to 288 kN (43,000 lbf). There was no visible cracking.

2. Hydrostatic load test by Fortier (*5*), 1954, Fresno, California; pipe diameter = 762 mm (30 in.); soil type, sandy loam/silica with cemented hardpan; f'_c = 15.2 MPa (2,200 psi); hydrostatic loadings; instrumented with Type IDP marsh gauge with a pressure range of 0 to 0.69 MPa (0 to 100 psi).

Test and results: A 13-ft test section was bulkheaded and hydrostatically loaded. A pipe rupture occurred at 229 kPa (33.2 psi) or 23.4 m (76.7 ft) of head.

3. Shallow burial test by Johnson and Hess (*6*), 1963, Tucson, Arizona; pipe diameter = 1219 mm (48 in.); in situ soil type, cemented sand and gravel; compacted fill around pipe at 100 percent compaction (ASTM T–180), 228 kg/m³ (143 pcf); cover, 0.15 m (0.5 feet); f'_c = 27.5 MPa (4,000 psi); truck axle and wheel loads; instrumented with strain gauges, dial gauges, and Carlson pressure cells.

Test and results: A maximum wheel load of 125 kN (28,000 lbf) was applied. No distress was observed visually or by instruments.

4. Shallow burial, early live load field test by Gabriel (*7*), 1964, Sacramento, California; pipe diameter = 1830 mm (72 in.); in situ soil type, partially cemented sandy silt; cover, 300

mm (12 in.); 3-day f'_c = 10.3 MPa (1,500 psi); truck axle loads; instrumented with deflection gauges.

Test and results: An axle load of 142 kN (32,000 lbf) was applied after 3 days. No distress was observed visually or by instruments.

5. Field load test by Gabriel (*8*), 1967, Sacramento, California; pipe diameter = 2134 mm (84 in.); in situ soil type, caliche hardpan; f'_c = 20.7 MPa (3,000 psi); early live loads with compaction equipment; instrumented with strain gauges and deflection gauges.

Test and results: Backfilled to 3.7 m (12 ft) and compacted with standard equipment 4 days after pipe was cast. No distress was observed visually or by instruments.

6. Shallow burial load test by Lum (*9*), 1969, Honolulu, Hawaii; pipe diameter = 610 mm (24 in.); in situ soil, stiff red clayey silt; 7-day f'_c = 22.7 MPa (3,292 psi); cover, 0.3 m (1 ft) over CMP, 0.0 to 0.3 m (0 to 1 ft) over concrete pipes; tractor-scraper wheel loads; instrumented with deflection gauges.

Test and results: A 200-kN (45,000-lbf) wheel load was moved over CIPCP, RCP (Class IV), and CMP. No distress was observed in concrete pipes; deflection of RCP was 8 to 10 times that of CIPCP. Large vertical and horizontal deflections of CMP were visually observed.

7. Zero cover static load tests and shallow cover, 0.3 m (1 ft), for dynamic tests by White and Underwood (*10*), Dallas, Texas, 1969; pipe diameter = 2440 mm (96 in.); f'_c = 40.9 MPa (5,920 psi); soil type, clayey sand; sand boxes (static tests) with hydraulic jacks, dynamic loads with falling weights; instrumented with strain and deflection gauges.

Tests and results: Static loads up 912 kN (205,000 lbf) were applied; no cracks were observed visually or by instruments. Dynamic loads up to 65 kN-M (48 ft-kps) were applied; no cracks were observed visually or by instruments.

8. Shallow burial field load test by Gabriel et al. (*11*), 1987–1988, Sacramento, California; pipe diameter = 1830 mm (72 in.); in situ soil type, hard silty clay; f'_c = 27.6 MPa (4,000 psi); cover: 0.5 m (20 in.); compaction equipment loading; instrumented with strain gauges, dial gauges, and pressure cells.

Test and results: Deflections and strains successfully measured the effects of 2+ times H2O loading. Instruments sensed a possible crack; however, none were observed visually.

CONCLUDING REMARKS

The success of CIPCP, as shown in the preceding section, offers evidence that when passive trench wall forces in the vicinity of the springline may be counted upon to develop an archlike response in the pipe to vertical loads, tensile stresses are kept below the cracking threshold. This permits economically efficient use of unreinforced concrete for culverts, pipelines, and other underground structures.

REFERENCES

1. *Recommendations for Cast-in-Place Nonreinforced Concrete Pipe*. ACI 346R–90. American Concrete Institute, Detroit, Mich.
2. *Cast-in-Place Concrete Pipe Process* (Lynch Manual). Tremont Equipment Co., Inc., Dixon, Calif., 1990.
3. Paris, J. M. Stress Coefficients for Large Horizontal Pipes. *Engineering News-Record*, Vol. 87, No. 19, Nov. 10, 1921, pp. 768–771.
4. Young, W. C. *Roark's Formulas for Stress and Strain*, 6th ed. McGraw-Hill Book Co., 1989.
5.* Fortier, E. C. *Tests on 30-inch No-Joint Concrete Pipe*. Unpublished report. Fresno, Calif., June 1954.
6. Johnson, M. A., and J. D. Hess. Load Testing of No-Joint Cast-in-Place Concrete Pipe, In *Highway Research Record 30*, HRB, National Research Council, Washington, D.C., 1963, pp. 20–40.
7.* Gabriel, L. H. *Load Testing of 72-Inch No-Joint Cast-in-Place Concrete Pipe with Shallow Cover*. Unpublished report. Sacramento State College Foundation, Sacramento, Calif., 1964.
8.* Gabriel, L. H. *A Study of Displacements of No-Joint 84-inch Cast-in-Place Pipe Soon After Construction*. Unpublished report. Sacramento State College Foundation, Sacramento, Calif., 1967.
9.* Lum, W. *Report of No-Joint Concrete Pipe Field Test Demonstration—Strength of 24-inch Pipe at Mililani Subdivision*. Unpublished report. Honolulu, Hawaii, Mar. 1969.
10.* White, A., and A. C. Underwood. *Field Sand Box Tests*. Unpublished report. Underwood and Associates, Houston, Tex., 1969.
11.* Gilley, C., L. Gabriel, and R. Standley. Field Test of 72 in.-Diameter Cast-in-Place Nonreinforced Concrete Pipe. Paper No. 26533. *Journal of Transportation Engineering*, ASCE, Vol. 118, No. 1, Jan./Feb. 1992.

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Field Performance of Cast-in-Place Nonreinforced Concrete Pipe

CURTISS W. GILLEY AND L. H. GABRIEL

A compilation of case histories of cast-in-place nonreinforced concrete pipe (a continuous monolithic cast underground conduit for irrigation water, storm water, sewage, and industrial waste) is presented. The results of field tests corroborate the value of passive restraint at the springline. Eight field studies dating back to 1954 demonstrate the load-carrying and hydrostatic capabilities of cast-in-place concrete pipe.

The case studies of nonreinforced cast-in-place concrete pipe (CIPCP) presented encompass a period of more than 38 years of in-service field experience.

By American Concrete Institute (ACI) Specification 346 definition, "CIPCP is an underground continuous nonreinforced concrete conduit, having no joints or seams, except as necessitated by construction requirements. It is intended for use to convey irrigation water, storm water, sewage, or industrial waste under a maximum internal operating head of 45 kPa (15 ft.) and external loads . . ." (*1*).

HISTORY OF CIPCP

Although a process for cast-in-place concrete pipe was first patented in 1897, it was not until the early 1920s that the Turlock Irrigation District in California's San Joaquin Valley pioneered its commercial use. Unlike today's machine monolithic casting process, these early pipes were hand (and later, machine) cast in two semicircular segments. Undesirable cold joints appeared at springline where the two segments joined.

The first modern casting machines was used in 1949. Because the function of these pipes in that year was for irrigation water, sizes were limited to 1220 mm (48 in.) in diameter. Application to storm sewer pipelines quickly followed in the early 1950s. Today, sizes with diameters of 610 mm (24 in.) through 3048 mm (120 in.) are routinely constructed. Approximately 3500 km (2,200 mi) of CIPCP has been installed to date, with approximately 22 percent with diameters of 1372 mm (54 in.) or larger. Most of the installations are located in California, Arizona, Texas, New Mexico, Oregon, and Washington. CIPCP has also been installed in Mexico City, Mexico, and Johannesburg, South Africa.

STRUCTURAL PERFORMANCE OF CONCRETE PIPE

The dominating characteristic of a brittle material, such as concrete, is a low threshold of tensile capability. For the reliable performance of concrete pipe, either the internal tensile forces must be transferred, through bond, to tough, ductile, steel reinforcing bars of large tensile capacity or the internal tensile forces must be significantly reduced by developing a compensating force field. Precast reinforced concrete pipe (RCP) is an example of the former; nonreinforced CIPCP is an example of the latter.

When responding to the application of loads, the pipe wall internal reacting forces of shear, in-plane thrust (wall thrust), and bending moment (wall bending) all contribute to the composite stress response. For rigid structures, such as concrete pipe, secondary stress effects due to deflections are assumed negligible; the deformed structure lies well within the bounds of small deflection theory.

The in-plane circumferential stress of wall thrust may be added arithmetically to the flexural stress of wall bending because both forces result in parallel stress fields that track the wall circumference. A properly designed and constructed CIPCP will enjoy an increase in the favorable wall thrust and a decrease in the unfavorable wall bending so as to mask, or nearly mask, the wall-bending tensile stress to which concrete is vulnerable. This is accomplished by the self-induction of passive lateral forces in the vicinity of springline when the lengthening horizontal diameter (under increasing load) engages the stiff walls of the trench which previously served as forms for the casting of the pipe. This is not unlike the way an arch structure develops lateral reaction forces at the supports, which serves to increase internal thrust and decrease internal bending. RCP, which does not enjoy the full benefits of the compensating effects of lateral support at springline, utilizes reinforcement to engage the high tensile stresses that result from wall bending.

CONSTRUCTION PROCEDURES

The first step in the construction process is to excavate a trench with vertical side walls and a round bottom, shaped with a round bottom bucket attached to a tracked excavator or backhoe. [For further information, see the Lynch Manual (*2*) pipe and trench detail, Figure 1, and Table 1.] Alignment is laser controlled.

The pipe casting machine (Figure 2) is placed in the trench, and its motor-driven winch system (Figure 3) is secured to an installed trench anchor. At the start of the process, and continuing in pace with the advancing casting machine, loose metal top forms shaping and containing the upper 270 degrees are positioned to receive concrete. Through a hopper that is integral with the casting machine, a low-slump 25- to 76-mm

C. W. Gilley, Tremont Equipment Co., Inc., 6940 Tremont Road, Dixon, Calif. 95620-9603. L. H. Gabriel, School of Engineering, California State University, 6000 J Street, Sacramento, Calif. 98519-2694.

Field Test of 72 in.-Diameter Cast-in-Place Nonreinforced Concrete Pipe[a]

By Curtiss W. Gilley,[1] Fellow, ASCE, Lester H. Gabriel,[2] Member, ASCE, and Robert S. Standley[3]

(Reviewed by the Pipeline Division)

Abstract: Monolithic nonreinforced cast-in-place concrete pipe (CIPCP) for storm drain, sewerage, and low-head irrigation pipelines has been in existence since 1954. This is a report on a field test of 72-in. inside diameter (ID) CIPCP with less than 2 ft cover and application of live loads exceeding 2 times H20-44 standard design highway loading. The test is directed and conducted at California State University at Sacramento for California Department of Transportation. The field test confirms the analytical model for satisfactory performance of the pipe under the conditions described.

Introduction

On September 10, 1987, a contract was awarded to the Foundation of California State University at Sacramento to design and execute full-scale field testing of a 72-in.-diameter cast-in-place concrete pipe (CIPCP). The purpose of the test program was to develop evidence as to the performance of CIPCP under minimum cover when subjected to highway loads at least as high as the standard H20-44. Soil samples were taken, and soil analyses were performed. Concrete cylinders and cores were prepared and tested. Suitability of the site and the in situ soil, a moist, firm, clayey silt over silty clay, was verified by means of a test pit. Live loads (wheel load) were certified.

The 72-in. CIPCP was chosen as being the most representative size of pipe for the product, which has a size range of 24–120 in.

The CIPCP of this study is a continuous single-stage monolithic concrete casting resulting in the manufacture and installation of nonreinforced concrete pipe used for storm, sewerage, and irrigation pipelines.

The machine used for the casting process for the 72-in.-diameter CIPCP of this study is shown in Fig. 1. The process utilized fixed and movable metal forms, the latter with mechanical tampers and internal vibrators to properly place and densify the concrete.

Response of Concrete Pipe

Because of the brittle nature of the material, successful performance of structural elements of concrete requires either a low threshold (or the ab-

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[1]Civ. Engr. and Pres., Tremont Equipment Co., 6940 Tremont Rd., Dixon, CA 95620.

[2]Prof. of Civ. Engrg., California State Univ. at Sacramento, Sacramento, CA 95819-2694.

[3]Adjunct Prof., California State Univ. at Sacramento, Sacramento, CA.

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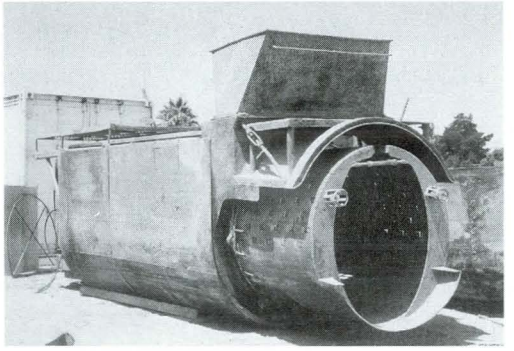

FIG. 1. 72-in. Diameter Movable Metal Form Casting Machine for Cast-in-Place Concrete Pipe

sence) of tensile stress, or the transfer of large tensile stresses from the concrete to tough, ductile fiber reinforcement of which steel reinforcement bars are the most notable example. The CIPCP of this study is an example of the former; reinforced concrete pipe (RCP) is an example of the latter.

Shear forces, in-plane thrust forces, and bending moments in the pipe wall all contribute to the stress response of the structure, when a pipe structure is resisting the application of load. For rigid structures such as concrete, secondary effects due to primary deflections are quite properly neglected; the deformed structure lies well within the bounds of small-deflection theory.

Since the stresses that arise as a consequence of the wall thrust force and the wall bending moment are both parallel and track the circumferential direction of the wall, these stresses are numerically additive. The wall thrust, due to outer wall loads, always results in compression only; the bending moment always results in both tension and compression. A properly designed and constructed CIPCP will have sufficient thrust compression stress (also known in flexible-pipe theory as "ring compression") to mask, at all points within the pipe wall, most (or all) of the flexurally induced tension stress.

To achieve this end, CIPCP is placed in the ground with passively constraining sidewalls, from approximately 25° above spring line on each side down through invert. This trench serves as forms for the casting of the concrete. See Fig. 2 for the standard section.

Any tendency for the pipe to elongate along its horizontal diameter will excite passive soil pressures in the trench walls that will create the appropriate load conditions for the reduction of the would-be bending effects. In much the same way, an arch structure develops lateral reaction thrusts that provide the same benefit. Without adequate sidewall passive capacity, this counter moment benefit may not be relied upon. Such is the case for all pipe, RCP and CIPCP included. In the case of RCP in a trench with sidewall backfill, this passive reaction is dominated by the backfill. For CIPCP, adequate sidewall passive capacity, may be expected from vertical trench-wall faces that become the external forms for the concrete pipe. The absence of tensile distress at crown and invert would be evidence of such operative passive forces in the vicinity of spring line. The test, in part, was designed

APPENDIX I. CONVERSION TO SI UNITS

To convert	To	Multiply by
in.	mm	25.4
ft.	m	0.3048
cu ft.	m^3	.0283
lb	kg	0.4536
lb force/ft	N/m	14.59
psi	MPa	0.00689
kips	kg	453.6

APPENDIX II. REFERENCES

"American Concrete Institute 346-90 Specifications & 346R-90 Recommendations for cast-in-place nonreinforced concrete pipe." (N/A). *Manual of concrete practice*, American Concrete Inst., Detroit, MI.

Paris, J. M. (1921). "Stress coefficients in large horizontal pipes." *Engineering News Record*, 8(19), 768–770.

Soil engineering. (N/A). Spangler and Handy Intext Educational Publishers.

Prediction Using fc' Actual

The design calculations used for prediction are based on $fc' = 3{,}000$ psi, the 28-day design strength of the concrete specified. In actuality, the design strength of the concrete 7 months after the 28-day breaks was determined to be 4,800 psi by the CALTRANS testing laboratory. Based upon this strength, the modulus of rupture is 624 psi. Safety factors for the 17-kip and 35.5-kip loads are 3.2 and 1.5, respectively.

Conclusions

1. The 72-in. diameter cast-in-place nonreinforced concrete pipe (CIPCP) constructed to the standard dimensions and material specifications for the product can be safely used under H20-44 highway loads with as little as 2 ft of cover, with or without pavement.
2. Normal backfilling of the pipe may be started when the minimum compressive stress of the concrete reaches 2,000 psi.
3. Performance of this product is dependent upon competent structural support from the in situ soil, which is assured by the construction-site requirements for the product. The properties of the soil at the test section met the established specifications of vertical free-standing trench walls through pipe zone and uniform, firm invert trench, for the in situ material. These practical standards for acceptable sidewall soil have been established by some 35 years of experience, and are described in specifications by American Concrete Institute and many state and local-agency standard specifications. The results verify the suitability of these standards for a normal H20-44 loading.

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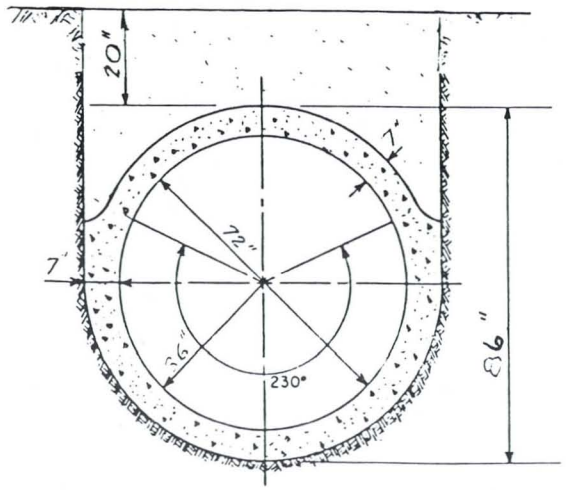


FIG. 2. Detail of Pipe Cross Section for 72-in.-Diameter CIPCP

to offer experimental evidence related to the formation and adequacy of these passive forces.

Construction

Trench excavation was completed on October 21, 1987. The trench was excavated with the special U-shaped bucket designed for 72-in. cast-in-place concrete pipe construction. The native soil at the site proved ideal for the purpose, permitting vertical trench walls with smooth-cut surfaces, and a firm uniform invert. A laser, installed at the end of the trench, was used by the tracked excavator operator to maintain line and grade using a target affixed to the bucket. Approximately 120 ft of trench bottom was finish-graded for the expected more than 80 ft of test pipe.

October 23, the pipe-casting machine was placed in the trench and secured to the winch cable at the north end of the trench. An engine in the front of the casting unit (pipe machine) provided power required to tamp and vibrate the concrete and winch the unit forward, south to north.

Transit-mix concrete (6 sack, 3,000 psi, 28-day design compressive strength, 1.5–2-in. slump, water-cement ratio of 0.49, 15% fly ash, and water reducer) was fed into a hopper, tamped, and vibrated to force the concrete down and around the steel mandrel. Smooth part-circle aluminum forms were placed inside to support the top two-thirds of the pipe. These 4-ft-long sections are fed through the casting machine just before the wet concrete emerges from the extruder. A workman behind the machine finish-troweled the exposed lower portion of the pipe (invert) as it was exposed.

Concrete was delivered in five transit-mix trucks. Test cylinders were taken from the first four trucks. (The last truck's concrete was not in a significant location.) Concrete from trucks 1–4 covered stations 0–12, 12–30, 30–48, and 48–66, respectively. The test section was at station 48 and therefore, used concrete from truckload No. 3. The concrete cylinder breaks for all cylinders tested ranged from 3,830 psi to 3,900 psi at the 28-day breaks.

Construction Load Tests

On October 26, test-cylinder breaks were made. The 72-hr compression strengths were 2,300–2,450 psi. Attainment of 2,000 psi strength is an established guideline for starting backfilling operations. Since this was met, backfilling was started south of the test section (station 48) from stations 0–30. The purpose was to demonstrate the pipe's ability to handle construction equipment and backfill dead loads at 2,000 psi compression strength. Native soil, a silty clay from the trench, was placed in lifts and compacted with a vibrating sheeps-foot roller to 20 in. of the pipe crown to relative density of 92.2% Caltrans test standard. A temporary crossing for the test load was graded at stations 12–20. A loaded gravel truck was driven across five times and then parked directly over the pipe for 15 minutes (Fig. 3). The pipe interior surface directly under the wheels was carefully inspected before and after the load test. There was no change or damage. The measured concentrated wheel load on the surface was 15 kips. The backfilling operations and the concentrated wheel load test verify the 2,000 psi criterion as a condition for proceeding with construction after completion of concrete casting.

Instrumentation

The strategy for the study of the performance of the pipe subjected to design loads no less than H20-44, included the following four systems of observation.

FIG. 3. Loaded Gravel Truck for 72-Hour Test

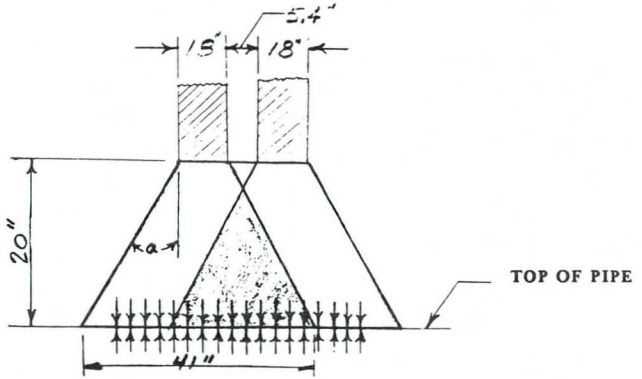


FIG. 12. Diagram of Rear Wheel Load Distribution for Field Test of 72-in. Diameter CIPCP

is greater than 1.20 × 35,500/5.37 = 7,930 lb/ft. The total vertical load is (V):

$$V = \text{LL} + W = 10{,}390 = 1{,}500 = 11{,}890 \text{ lb/ft} \quad (18)$$

The moment for this heavier load is

$$M = 0.125VR = 0.125(11{,}890)3.29 = 4890 \text{ ft-lb/ft} \quad (19)$$

Including the same (as for the earlier calculation of front-wheel load) effects of lateral forces and weight of pipe, the maximum moment = 4,890 − 590 − 1,350 + 410 = 3,360 ft-lb/ft, resulting in a maximum tensile stress of:

$$\frac{-T}{12t} + \frac{6M}{t^2} = \frac{-2{,}240}{12 \times 7} + \frac{6 \times 3{,}360}{7^2} = 385 \text{ psi} \quad (20)$$

for a factor of safety based on rupture modulus = 1.2. Distress is not predicted for the CIPCP with a dual-wheel load of 35.5 kips, nor did it occur.

Pipe Filled with Water

As a comment, although the test pipe was not filled with water, it is interesting to note that, had the pipe been carrying a full load of water (exclusive of head), it still is predicted to perform well. The thrust and moment:

$$\text{Thrust } (T) = -0.451W = -0.451(1{,}765) = -800 \text{ lb/ft} \quad (21)$$

$$\text{Moment } (Mw) = 0.070R = 0.070(1{,}765)3.29 - -410 \text{ ft-lb/ft} \quad (22)$$

For the case of the dual rear wheels, the maximum tensile stress is:

$$\frac{-2{,}240 - 800}{2 \times 7} + 6 \times \frac{3{,}360 + 410}{7^2} = 445 \text{ psi} \quad (23)$$

The safety factor based on rupture modulus is 1.1.

to Z_u (ft-lbs/ft of pipe length); T_{lt} = thrust in the pipe wall due to Z_t (lbs/ft of pipe length); M_{lt} = moment in the pipe wall due to Z_t (ft-lbs/ft of pipe length); and R = radius to center of pipe wall (ft).

a. Rectangular pressure distribution.

Thrust $(T_{lu}) = 1.0(Z_u)(R) = 1.0(kw'H)R = 1.0(1 \times 110 \times 1.67)(3.29)$

$= 550$ lb/ft min $= 1.0\ (1 \times 130 \times 1.67)(3.29) = 710$ lb/ft max ..... (7)

Moment $(M_{lt}) = -0.250(Z_u)R\hat{}2 = -0.250(1 \times 130 \times 1.67)$

$\times\ (3.29)\hat{}2 = -590$ ft-lb/ft ..... (8)

b. Triangular pressure distribution.

Thrust $(T_{lt}) = 1.375(Z_t)R\hat{}2 = 1.375(kw')R\hat{}2 = 1.375(1 \times 110)(3.29)\hat{}2$

$= 1{,}640$ lb/ft min $= 1.375(1 \times 130)(3.29)\hat{}2 = 1{,}930$ lb/ft max ..... (9)

Moment $(M_{lt}) = -0.292(Z_t)R\hat{}3 = -0.292(1 \times 130)(3.29)\hat{}3$

$= -1{,}350$ ft-lb/ft ..... (10)

3. Dead weight of pipe.

Thrust $(T_p) = 0.027(W_p) = 0.027(1{,}790) = 550$ lb/ft ..... (11)

Moment $(M_p) = 0.070(W_p)\mathrm{R} = 0.070(1{,}790)3.29 = 710$ ft-lb/ft .... (12)

Totals (exclusive of water in the pipe):

T(min) = Thrust(min soil wt) $= 0 + 550 + 1{,}640 + 50$

$= 2{,}240$ lb/ft ..... (13)

T(max) = Thrust(max soil wt) $= 0 + 710 + 1{,}930 + 50$

$= 2{,}690$ lb/ft ..... (14)

M = Moment $= 3{,}060 - 590 - 1{,}350 + 410 = 1{,}530$ ft-lb/ft ..... (15)

Maximum stress:

$$f = \frac{-T(\mathrm{min})}{12t} + \frac{617}{t\hat{}2} \quad \text{..... (16)}$$

$$f = \frac{2240}{-12 \times 7} + \frac{6 \times 1530}{(7)\hat{}2} = 161 \text{ psi} \quad \text{..... (17)}$$

With a modulus of rupture for $fc' = 3{,}000$ psi concrete taken at 492 psi, the factor of safety = 3.0. The 17.0-kip wheel load is predicted to cause no distress to the CIPCP, nor did it. Modulus of rupture is taken as 9.0 $\sqrt{fc'}$ (*ACI Materials Journal*, 1990).

Rear-Wheel Analysis

In Fig. 12, note that each of the 18-in. dual wheels, spaced 5.4 in. apart, will distribute the live load a distance of 41 in. along the crown of the pipe, when the angle with the vertical is 30°. For a 35.5-kip dual-wheel load, the effective crown-line load, $(2 \times 17.75 \times 12 \times 1{,}000)/41 = 10{,}390$, which

Visual Inspection

Visual inspection of the interior of the pipe, for evidence of tension cracks, was performed after the placement and removal of the test loads. On the assumption that, in regions of maximum tension (on the interior wall of the pipe, these occur at crown and invert), cracks may form under live load and then close with the withdrawal of the live load from the pipe, a special effort was made to discover evidence of such cracking. To this end these areas were first wet down and then surface-dried. Any tension cracks that may have closed with the withdrawal of load would be expected to show evidence of such cracking due to the capillary draw of water into the crack. The wetting fluid was water-treated with a mild detergent (Fotoflo 200) for the purposes of breaking the surface tension, thereby enhancing the opportunity for the wetting fluid to be drawn into the crack, should cracks be present.

Interface Pressure

Five pressure sensors were positioned in a plane normal to the longitudinal axis of the pipe. Two of these sensors, at 5 and 7 o'clock positions, were placed at the soil-pipe interface soon after the excavation of the trench (October 22) and prior to the placement of the concrete (October 23). The remaining three pressure sensors, at 3, 9, and 12 o'clock positions, were installed on October 27 in the soil in preformed pockets.

Tangential Strains—Inner Pipe Wall

At 24 points around the inner pipe wall surface at approximately every 15° measured clockwise from the crown, a circumferential strain gage was glued to the pipe wall (see Fig. 4). Each gage was calibrated to read directly in microin. of strain. A harness of connecting wires lead to a multichannel switching and balancing unit and digital recording readout instrument, external to the pipe.

loc.	X-cord	Y-cord
1	9.21	35.75
2	17.34	32.48
3	25.65	25.78
4	30.75	18.51
5	34.73	8.73
6	35.74	0.15
7	34.78	-9.16
8	30.55	-18.83
9	25.72	-25.56
10	19.17	-30.82
11	8.91	-35.20
12	0.39	-36.64
13	-8.30	-35.54
14	-17.67	-31.82
15	-25.07	-26.29
16	-31.13	-18.84
17	-35.25	-10.04
18	-36.41	-0.63
19	-35.78	7.14
20	-31.48	19.11
21	-26.84	25.38
22	-19.83	31.40
23	-10.57	35.39
24	0.00	36.50

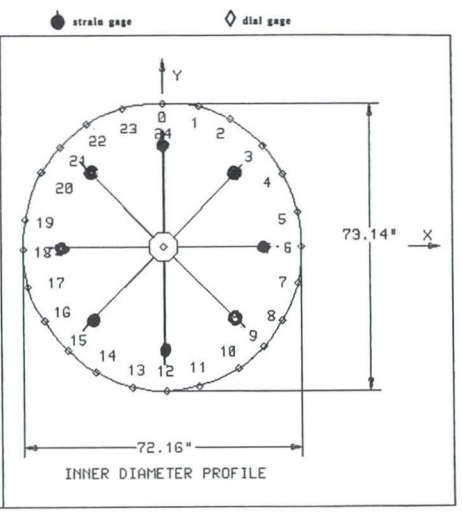


FIG. 4. Location of Strain Gages and Dial Gages

Radial Displacements—Inner Pipe Wall

At eight points around the inner pipe wall surface, at approximately every 45° measured clockwise from the crown, a mechanical spring-loaded dial gage (see Fig. 4), with a least count of 0.0001 in., was positioned to sense the radial displacement of the inner wall of the pipe. The planes of the dial gages and strain gages were sufficiently close (less than 3 in. apart) to be considered coincident. This coincident plane will, in the future, be referred to as the plane of instrument.

The dial gages were each mounted at the end of one of eight spokes radiating from a central hub. The hub was positioned at the center of the inner-wall circle and was supported by a truss-like frame with a base of approximately 22 ft [see Figs. 5(*a*) and 5(*b*)]. Smooth tungsten carbide steel tabs were positioned and glued on the inner wall of the pipe so as to receive the sensing probe of the gage. Enough adjustment potential was built into the system of base, truss, hub, spokes, and gage so as to permit the noted and desired alignment. During the source of the test, the gages were read using a surveyor's transit telescope positioned outside the pipe.

The Test

Intermittent wet weather and wet soils in the test area prevented sufficient time to set up the actual instrumented testing until June of the next year.

On June 22, 1988, the instrumented pipe was live-load tested with an off-highway Euclid RX 35 loaded with aggregate base material to that point where the front axle registered 32 kips (a more critical single-wheel loading than the standard H20-44 dual-wheel loading). The rear-axle loading registered more than twice the standard H20-44 with a maximum dual-wheel load of 35.5 kips.

The latter is the maximum load that was placed directly over the pipe (see Fig. 6). Wheel loads were measured at the site by the California Highway Patrol using standard portable scales.

Live-load testing was started at 1:30 P.M. Three load positions were employed.

1. Front wheels on pipe centerline with right front wheel directly over the instrumented X-section.
2. Front wheels on pipe centerline and centered over the instrumented X-section.
3. Rear right dual wheels on pipe centerline and centered over the instrumented X-section.

Monitoring the instrument readout during loadings clearly showed that load position 1 produced a greater stress than position 2. As previously planned, this same position was used with the heavier rear wheels as the critical test load. The truck was run back and forth several times, then parked in position 3 for approximately 30 minutes while readings and observations were made.

Visual observations and gage readings indicated no distress whatever in the pipe. Since the structure has passed proof load testing (more than twice an H20-44 wheel load, less than 2 ft of cover, unpaved road) no further tests were made.

Following testing, soil borings were taken alongside the pipe to obtain data on the in situ material outside the trench. The materials were consistent

These same arguments apply for calculation of net moment at invert. Consistent with this, a conservative estimate of the Rankine coefficient of lateral pressure is taken equal to 1 for the purposes of this calculation. Usually a Rankine coefficient of active pressure (0.33) is used in determining the lateral forces at spring line. This is judged to be overly conservative in this prediction calculation in that it is not possible to have active pressure operating against the sidewall of the CIPCP, but undoubtedly reassuring to users.

Analysis for Stresses

The maximum thrust and moment of the pipe section are separately calculated and subsequently added. The conditions of loading follow.

1. Vertical line loads at crown.
   a. Live load.
   b. Earth load above crown.

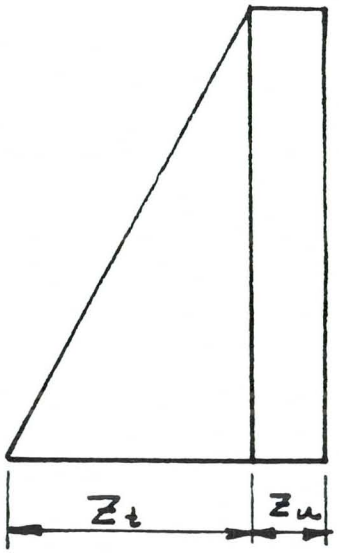
Thrust (T_v) = 0 ..... (5)

due to symmetry of loads and geometry.

Moment (M_v) = $0.125VR$ = 0.125(7,450 lb/ft)(3.29 ft)

= 3,060 ft-lb/ft ..... (6)

2. Lateral line loads at spring line (see Fig. 11), where T_{lu} = thrust in the pipe wall due to Z_u (lbs/ft of pipe length); M_{lu} = moment in the pipe wall due



Lateral Soil Pressure Diagram

FIG. 11. Lateral Soil Pressure Diagram

$$W = C_d w B^2 \quad \ldots\ldots (2)$$

where C_d = ditch coefficient = 0.22, for H/B = 1.67/7.25 = 0.23; H = height above crown; and B = trench width.

The trench soil, a slightly moist, firm-to-hard, brown clayey silt has a unit weight of $110 < w < 130$ pcf. Using the large value, the earth load is:

$$W_e = 0.22 \times 130 \times \frac{87}{12^2} = 1{,}500 \text{ lb/ft} \quad \ldots\ldots (3)$$

The dead weight of the 72-in. diameter CIPCP W_p = 1,790 lb/ft.

The sum of the live and earth loads (V) is

$$V = \text{LL} + W_e = 5{,}950 + 1{,}500 = 7{,}450 \text{ lb/ft} \quad \ldots\ldots (4)$$

Lateral Loads

In the construction of CIPCP, the trench walls and bottom are the forms against which the concrete is cast. Prior to the surface loading of the pipe-soil composite, the self-standing sidewalls neither lean against the pipe (active pressure) nor are they leaned upon by the concrete pipe (passive pressure). When load is placed on the pipe-soil composite (directly above the pipe) on line with the pipe's vertical centerline, the response of the pipe is a slight shortening of the vertical diameter and a correspondingly small lengthening of the horizontal diameter. The effect is to create a lateral passive pressure at the pipe-soil interface of magnitude bounded by the at-rest pressure and full passive pressure. For reasons explained immediately following, the lowest pressure (at rest) is the most conservative and adopted for this study.

Assume that the top portion of the CIPCP works as a structural arch as noted in Fig. 10. The vertical load at the crown represents the sum of the live and earth loads. The lateral thrust, a consequence of active earth pressure (Rankine coefficient >1), is applied at spring line. From equilibrium, it is noted that the vertical reactions ($W/2$) are independent of the lateral thrust (H) and bending moment (M), given symmetry of loads and reactions. Whatever moment H and M excite at other points (say about the crown), is reduced by a moment of opposite sense excited by the spring-line thrusts. For an arch of the geometry noted in Fig. 10, the greater the value of H, the lesser the net moment, illustrating the structural efficiency of the arch.

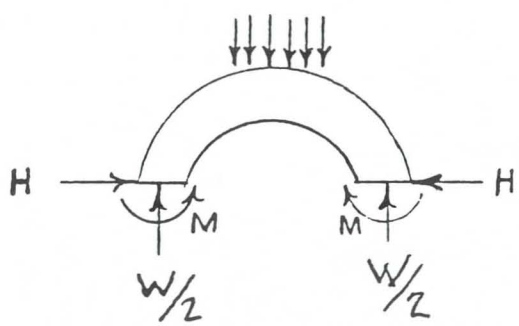


FIG. 10. Plot of Forces Acting on Top Half of 72-in. CIPCP

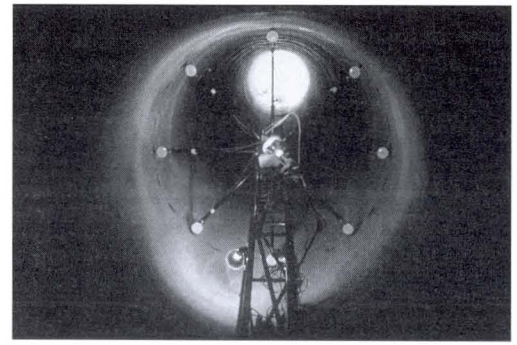


FIG. 5(*a*). Dail Gages and Support Frame

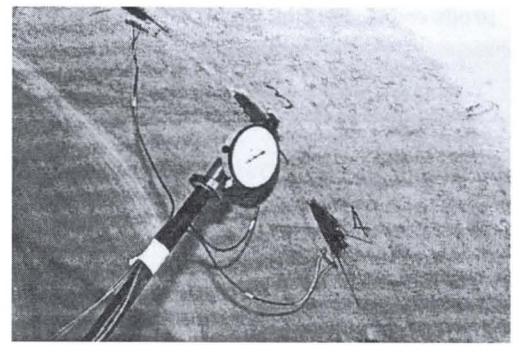


FIG. 5(*b*). Detail of Dial Gages and Strain Gages

FIG. 6. Loaded Off Road Vehicle for Strength Test

with the initial soil sampling in the trench area, namely clayey silt over silty clay. In-place soil densities varied from 99 pcf to 109 pcf with initial tangential modulus values from 800 to 4,200.

Experimental Results

The experimental results of the study offer a very compelling statement as to the capabilities of the test section, as a reasonable representative of CIPCP, to successfully resist the unusually large test wheel load of more than 35,500 lb (more than twice the 16,000 lb maximum wheel load of the H20-44 highway design load). As will be described in more detail, the visual qualitative test results, the quantitative displacement-gage measurements of radial displacement, and the quantitative strain-gage measurements of inner-wall circumferential strain all confirm the successful response of the pipe.

The pressure sensors, however, did not successfully measure the interface pressures at the five points previously noted in the section on instrumentation. It is important in experimental design to introduce redundant systems of measurement in anticipation of failure of any one system—an event that often takes place. In this study, three systems of measurement were introduced. The strain-gage system of measurement correlated with the displacement system of measurement. The pressure system of measurement failed. The sensor at 12 o'clock was the victim of an open circuit. The other four sensors just did not respond to the interface pressures known to be acting. It is believed that the long period between the time of installation of the pressure sensors (late October 1987), and the time of the load test (early June 1988), may have been responsible for the difficulty. Minor soil settlements, in part due to the rains, which included minor flooding, followed by the necessary subsequent surface regrading, are believed to have caused a disturbance to the previously secure contacts between the sensing face of the pressure gage and the material to be sensed at the interface. It is worth noting that the other instrumentation systems of mechanical displacement gages and electrical strain gages were installed only one day prior to the test.

For the following, all measurements of reference are taken at the test section along the inner circumference of the pipe, measured clockwise from the crown as viewed from north to south.

Attention is now drawn to Table 1 and to Fig. 7 wherein circumferential strains are plotted against location. Note the orderliness of the unsmoothed raw strain readings. The largest tension strains occur, as expected, in the vicinities of the crown (0°) and invert (180°). At the haunch, spring line, and some distance below spring line, the expected fields of compression are noted. Also note that the strains from the 35.5-kips wheel load are approximately double those from the 17-kips wheel load. The tensile strains at the crown indicate maximum tensile stress levels in the order of 60–70 psi and 120–140 psi for the 17-kips and 35.5-kips wheel loads, respectively. These stress levels are less than those predicted by the standard industry calculations. The stresses predicted by analysis are 161 psi and 385 psi respectively for the 17-kips and 35.5-kips loads. The difference is a reflection of the conservative nature of the design.

The radial displacements are listed in Table 2 and are plotted versus location on Fig. 8. Note at first, that the displacements are very small, indeed, and that the maximum radial displacement is at the crown and of a magnitude of approximately 0.004 in. inward for the 35.5-kips wheel load,

live and dead loads at the crown and the horizontal load acting at spring line. Other loads considered are the dead weight of the pipe and the water load within the pipe. This latter is included for discussion, but it does not represent the case of the field test of this report. Design values of concrete strength and geometry are used.

Loads

The live load on the pipe was delivered by a Euclid R35 off-road hauler. The tire size for this hauler is 1800-33, 18 in. wide with rated pressure of 65 psi.

The front axle of the hauler has two wheels; the rear axle has two sets of duals, each wheel of each dual being 5.25 in. clear distance from its companion wheel. The front wheel placed over the test section carried a load of 17.0 kips; the rear dual placed over the test section carried a two-wheel load of 35.5 kips. The wheels of each test section were oriented normal to the longitudinal axis of the pipe.

Front-Wheel Analysis

Vertical Loads

It is common practice to assume that a surface wheel will, for a short length of pipe, load the pipe with a uniform line load acting at the crown. The loading cone shown in Fig. 9 may reasonably lie within those values calculated for $30° < a < 45°$.

An impact factor of 20% increases the 17.0-kips load to 20.4-kips.

Using the conservative estimate $a = 30°$, the live load (LL) is calculated as:

$$LL = \frac{20.4}{1.5 + (2 \times 1.67 \times \tan 30°)} = 5{,}950 \text{ lb/ft} \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Using Marston's Theory for earth loading,

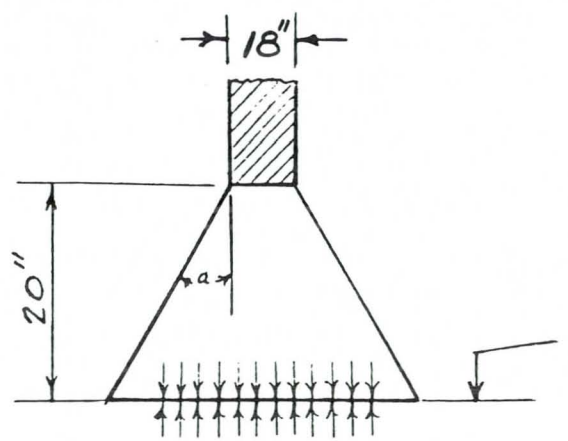


FIG. 9. Diagram of Wheel Load Distribution to 72-in. CIPCP

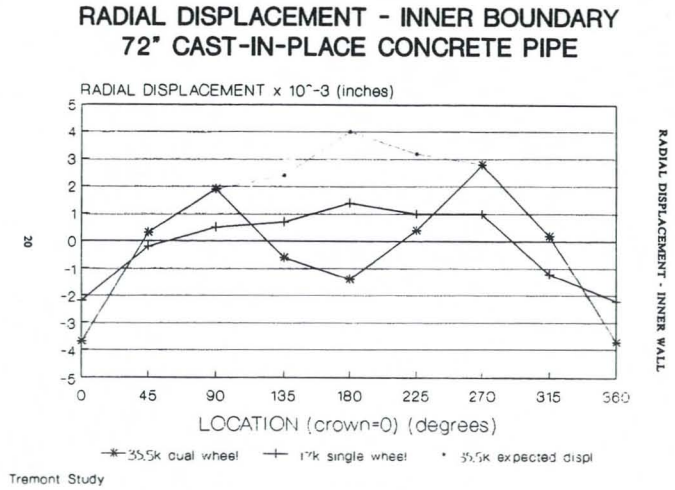


FIG. 8. Plot of Radial Displacement—Inner Boundary 72-in. CIPCP

event that did not take place. The cross-section of the CIPCP, a highly redundant structural element, has a great deal of reserve capacity beyond the formation of a fully developed plastic hinge at invert. Two hinges, say at invert and crown, transform the cross section into two stable two-hinged arches. Two more hinges, say in the vicinity of the spring line on each side of the pipe, transform the cross section into two stable three-hinged arches. The conclusion drawn is that a significant reserve capacity exists in this test pipe even after the application of the 35-kip concentrated dual-wheel load.

2. At some level of load, a threshold is crossed beyond which increasing interface shear in the vicinity of spring line exceeds the capacity of the interacting walls of concrete and soil trench. At this point, some vertical interface slippage occurs, which is resisted more competently at invert than at any point between spring line and invert. This phenomenon would result in a reversal of curvature, the event still wholly contained within the elastic response of the structure (as evidenced by the very small movement and the absence of cracks).

In either case, the conclusion drawn is that the pipe has significant reserve capacity after the application of the 35.5-kips concentrated dual-wheel load.

Analytical Predictions

It is the purpose of this section to illustrate that the performance of CIPCP may be anticipated by calculation. The calculations that follow are standard moment and thrust calculations utilizing Paris ring coefficients (Paris 1921).

The principle of the analysis is to calculate the maximum bending moment and normal thrust force in the pipe wall, and then to algebraically add the bending tension stress to the thrust compression stress. This yields the largest magnitude of tension in the pipe wall, a value that is compared with the modulus of rupture for the concrete (appropriate for nonreinforced concrete where bending dominates the stress field). A factor of safety against failure is calculated.

The loads on the pipe are conservatively taken as line loads, the vertical

TABLE 1. Circumferential Strains

Gage Number (1)	Location (degrees) (2)	Strain: 17k on Instrument Line			Strain: 35k on Instrument Line		
		Zero (3)	Load (4)	Strain 10^{-3} (in.) (5)	Zero (6)	Load (7)	Strain 10^{-3} (in.) (8)
24	0.00	−0.004	0.016	0.02	0	0.038	0.038
1	14.57	−0.001	0.006	0.007	−0.002	0.016	0.018
2	28.38	0	−0.009	−0.009	−0.002	−0.011	−0.009
3	45.26	−0.001	−0.018	−0.017	−0.004	−0.03	−0.026
4	60.22	−0.001	−0.013	0.012	−0.002	−0.025	−0.023
5	76.91	−0.001	−0.01	−0.009	−0.003	−0.023	−0.02
6	90.53	−0.001	−0.009	−0.008	−0.003	−0.022	−0.019
7	105.29	0	−0.004	−0.004	−0.002	−0.012	−0.01
8	121.98	0.002	0.002	0	−0.001	0	0.001
9	135.02	−0.002	−0.001	0.001	−0.002	−0.001	0.001
10	148.24	0.001	0.004	0.003	0.002	0.006	0.004
11	165.90	−0.002	0.003	0.005	−0.002	0.006	0.008
12	179.51	−0.003	0	0.003	−0.004	0.004	0.008
13	193.32	−0.001	0.002	0.003	0	0.008	0.008
14	210.20	0	0.001	0.001	−0.002	0.001	0.003
15	224.78	−0.002	−0.001	0.001	−0.005	−0.004	0.001
16	239.93	0	−0.003	−0.003	−0.004	−0.007	−0.003
17	255.27	−0.003	−0.006	−0.003	−0.004	−0.013	−0.009
18	270.23	−0.001	−0.008	−0.007	−0.003	−0.019	−0.016
19	282.49	−0.002	−0.011	−0.009	−0.003	−0.021	−0.018
20	302.67	−0.002	−0.014	−0.012	−0.003	−0.029	−0.026
21	314.94	−0.002	−0.014	−0.012	−0.003	−0.027	−0.024
22	329.51	−0.003	−0.008	−0.005	−0.002	−0.014	−0.012
23	345.43	−0.001	0.006	0.007	−0.004	−0.015	−0.011
24	360.00	−0.004	0.016	0.02	0	−0.038	0.038

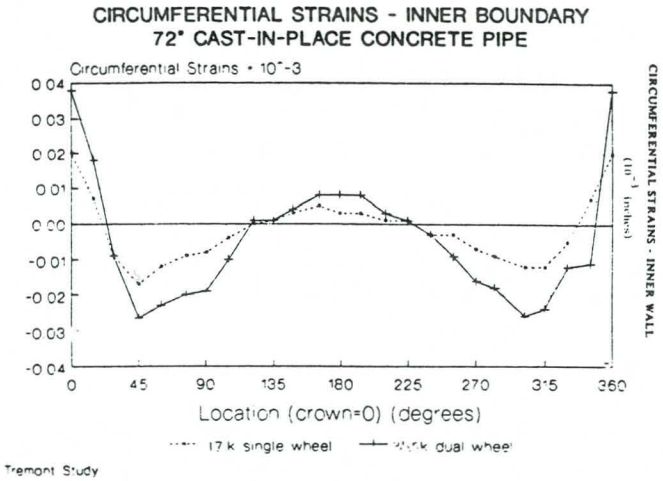


FIG. 7. Plot of Circumferential Strains—Inner Boundary 72-in. CIPCP

and one-half that for the 17.0-kips wheel load. This low level of displacement is compatible wiht the performance of a very stiff soil-pipe response.

A study of the response of the test of the 17.0-kip wheel load (6.5% greater than the standard H20-44) shows the total vertical diameter shortening, rigid-body motion culled out, is approximately 0.0008 in. (0.0022 inward at the crown and 0.0014 outward at the invert). This remarkably low level of deformation response points to the likelihood that it is the whole soil-structure composite that is supporting the active live load. This favorable attribute is judged to be created, in large part, by the intimate contact between the outer pipe wall and the wall of the trench at the interface where the two meet. The passive soil thrusts in the vicinity of the spring line create the counter moments in the pipe wall needed to reduce the tension otherwise created by the wall bending moments.

Attention is drawn to the radial deformation response of the pipe when subjected to the 35.5-kips wheel load (122% greater than the standard H20-44) (see Fig. 8). Note that between crown and spring line (0°–90° and 270–360°) the patterns of radial deformation (solid lines) are such that the recorded displacements of the 17.0-kips and 35.5-kips concentrated loads track one another. Between spring line and invert, the pattern for the 35.5-kips load abruptly changes; the invert moves inward rather than outward. This pattern may be explained by a change in curvature of the pipe shell in the vicinity of the invert, with its effects being registered at 135°, 180°, and 225°. The dotted line in the figure is simply conjecture as to what radial deformations might have occurred in the absence of such a phenomenon.

Very careful and repeated visual inspection of crown and invert revealed no tension cracks. Also, note the low order to the magnitude of the numbers; a measured 0.0015 in. inward at the invert as contrasted with the conjectured 0.0040 in. outward at the invert.

Two possible explanations for this change in curvature are offered:

1. A plastic hinge, at invert, was in the proces of forming. Had a fully formed plastic hinge resulted, it is reasonable to expect tension cracks at the invert, an

TABLE 2. Radial Displacements

Gage Number (1)	Location (degrees) (2)	Deflection: 17k on Instrument Line			Deflections: 35k on Instrument Line		
		Zero (3)	Load (4)	DISPL (in.) (5)	Zero (6)	Load (7)	DISPL (in.) (8)
24	0	0.2019	0.2041	−0.0022	0.2031	0.2068	−0.0037
3	45	0.2017	0.2019	−0.0002	0.2031	0.2028	0.0003
6	90	0.2013	0.2008	0.0005	0.2022	0.2003	0.0019
9	135	0.2192	0.2185	0.0007	0.219	0.2196	−0.0006
12	180	0.2188	0.2174	0.0014	0.2175	0.2189	−0.0014
15	225	0.2181	0.2171	0.001	0.2168	0.2164	0.0004
18	270	0.2188	0.2178	0.001	0.218	0.2152	0.0028
21	315	0.2007	0.2019	−0.0012	0.2012	0.201	0.0002
24	360	0.2019	0.2041	−0.0022	0.2031	0.2068	−0.0037