UNI-BELL TECHNICAL REPORT

SUSTAINABLE PIPE INFRASTRUCTURE –
IT'S OUR RESPONSIBILITY

DEFLECTION:
THE PIPE/SOIL MECHANISM

Prepared by the

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ABSTRACT

PVC sewer pipe is properly termed flexible pipe. As a well designed "flexible conduit," PVC sewer pipe derives exceptional soil load carrying capability from its flexibility, i.e., capacity to strain.

Proper understanding of flexible conduit theory is required to appreciate the effective performance of the pipe/soil system inherent in the response of buried flexible pipe to imposed loads.

The deflection mechanism effectively transfers the vertical force vectors derived from the load into approximately horizontal force vectors which are, in turn, opposed by opposite and equal reactions derived from the side support soil.

Long-term deflection of buried PVC sewer pipe can be predicted with acceptable accuracy. Proper system design and acceptable installation practice can effectively maintain PVC sewer pipe within desired limits. Research and field evaluation data demonstrate that these products will not experience structural failure at deflections equal to or less than 30 percent of base inside diameters.

A safety factor of 4:1 was selected in developing the recommended maximum deflection limit of 7.5 percent.

Engineers and contractors in general have come to realize that deflection in PVC sewer pipe is not a source of fear, but rather a source of significant benefit.

THE PIPE/SOIL MECHANISM

The acceptance of PVC sewer pipe, which at one time was considered innovative in sewer and sanitary districts, has now become commonplace. More than 90 percent of all sanitary sewer pipe, 15 inch and smaller, being installed in North America today is PVC.

The general acceptance of PVC sewer pipe is based on a solid foundation of good experience in the field. A substantial element of the experience with PVC sewer pipe has been developed through extensive evaluation of the deflection process. This report is dedicated to the review and analysis of deflection in buried PVC sewer pipe while providing engineering recommendations considered appropriate to insure that the deflection mechanism is harnessed to provide optimum benefits.

PVC sewer pipe is properly termed a "flexible conduit." On a worldwide basis, a "flexible conduit" is generally defined as a pipe which will deflect at least 2 percent without any sign of structural distress -- such as rupture or cracking.[6] Flexible pipe, such as PVC sewer pipe, which can deflect substantially more than 2 percent, derives exceptional soil load carrying capability from its flexibility.

Deflection of buried flexible pipe has been a phenomenon which has inspired both confidence and fear. PVC sewer pipe proponents explain with enthusiasm that PVC sewer pipe must deflect to function properly as a flexible pipe in the ground providing acceptable long-term performance. PVC sewer pipe opponents have expressed their great concerns that deflection could be considered the measure of product failure.

The term, "flexible," may be properly defined as "able to bend without breaking; not stiff or rigid;" "flexible" may also mean "adjustable to change."[1] The engineering profession has long recognized the benefits of flexibility in the design of structures and machines. Countless examples of proper performance derived through engineering design based on controlled flexibility surround us (e.g., suspension bridges, "skyscrapers," towers, ships, airplanes and flexible pipe).

PVC sewer pipe is a product of modern technology. As with numerous other benefits of technology, it cannot be accepted and used to proper advantage without understanding. Such understanding must be developed through proper evaluation of the technology, through comprehensive research in laboratories, and through extensive investigation and evaluation of field performance. This report will consider PVC sewer pipe technology, the research which supports it and the field experience which substantiates its reliability.

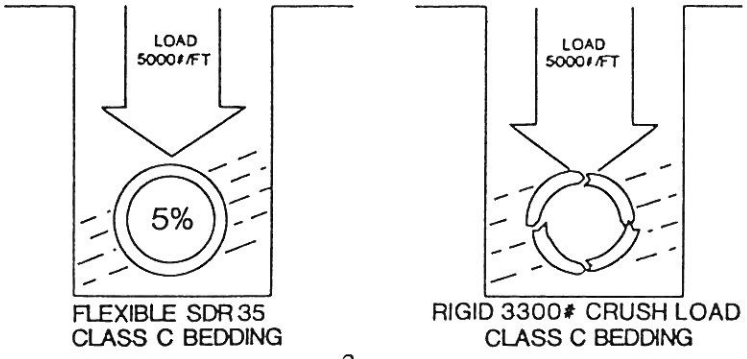
Of course, it is not difficult to accept the premise that flexibility in sanitary sewer pipe could be a source of benefit. However, the immediate question is obvious. How much deflection can be considered beneficial, and how much can be considered too much? The answers to these questions require an understanding of flexible conduit materials and theory.

FLEXIBLE CONDUIT THEORY

A flexible pipe derives its soil carrying capability from its flexibility.[2] The buried pipe under load tends to deflect. The deflection mechanism effectively transfers the vertical force vectors derived from the load into approximately horizontal force vectors which are, in turn, opposed by opposite and equal reactions derived from the side support soil. While the deflection mechanism is developing passive soil support at the sides of the flexible pipe, the ring deflection relieves the pipe of the major portion of the vertical soil load which is then carried by the surrounding soil through the mechanism of an arching action over the pipe.[6]

The effective strength of the pipe/soil system is remarkably high. Laboratory tests conducted in soil cells at Utah State University substantiate this point. Rigid pipe with a three-edge bearing strength of 3300 lb/ft (48.15 kN/m) was buried in Class C bedding and then exposed to an effective soil load of 5000 lb/ft (72.95 kN/m). Under this load, which is typical at trench depths from 45 to 50 feet (13.7 - 15.2 m), the pipe failed. This failure, of course, is no discredit to the rigid pipe product, since its design strength was far exceeded by the imposed load. Under identical soil conditions, PVC sewer pipe with a minimum pipe stiffness of 46 psi deflected 5 percent.[6] See Figure 1. The design performance limits for PVC sewer pipe related to deflection are far in excess of the 5 percent deflection realized in this laboratory evaluation.[3] Field experience with this PVC sewer pipe product installed in sanitary sewer systems throughout North America further reinforces the laboratory research and theoretical computations which predict that, through the deflection mechanism, PVC sewer pipe can provide long-term reliability and durability.[7]

FIGURE 1
EFFECTIVE STRENGTH OF A FLEXIBLE PIPE



Dr. M. G. Spangler, in 1941, observed that the theory of loads on buried pipe, as commonly used in the design of rigid sewer piping systems, is not adequate for flexible piping system design.[2] Spangler noted that flexible pipe may provide relatively little inherent strength in comparison with common rigid pipes as demonstrated by testing for three-edge bearing strength; yet, when buried, a significant ability to support vertical loads is derived by its performance as a flexible conduit with controlled deflection in a pipe/soil system. A common reaction to his research findings, then, is not uncommon today. Engineers unfamiliar with the performance of buried flexible pipe are reluctant to depend upon design strength derived from a pipe/soil system. As evidenced in design of many engineered structures -- such as bridges, buildings, dams, highways and canals -- reliable long-term strength and durability can be achieved and maintained through dependence on a combined strength of a structure/soil system derived when equilibrium between the soil and the structure is attained. Through his brilliant work, Dr. Spangler laid the foundation upon which flexible conduit theory has been developed. Design and installation of PVC sewer pipe systems today are based on the need to assure equilibrium between PVC pipe and embedment soil, thereby assuring the strength and durability of a pipe/soil system. Such design, of course, must be based on flexible conduit theory.

Equilibrium is achieved between PVC sewer pipe and its embedment soil when the rate of change in deflection becomes asymptotic to time.[8] At this point, which can occur after days, weeks or months depending on installation conditions, changes in deflection of the buried pipe cease to occur. The pipe/soil system has achieved equilibrium. It is obvious, then, that deflection is desirable, but must be maintained within acceptable limits.

The amount of deflection that will occur in any buried flexible pipe depends on three factors:

- Pipe Stiffness
- Soil Stiffness
- Load on the Pipe - both earth load and live load[9]

Before attempting to analyze the proper deflection limit for PVC sewer pipe, it is appropriate that we evaluate the factors which influence deflection in flexible pipe.

Pipe Stiffness. Pipe stiffness is generally defined as $\frac{F}{\Delta Y}$. (See Equation 1.) Pipe stiffness, as a value for a specific flexible pipe, is the unit load required to produce deflection in parallel plate loading to an arbitrary datum, usually 5 percent.[10] Pipe stiffness is measured in accordance with procedures established in ASTM D 2412, Standard Test Method for Determination of External Loading Characteristics of Plastic Pipe by Parallel-Plate Loading.[4]

It must be emphasized that the test to determine three-edge bearing strength does not provide meaningful data for flexible pipe.[6] Three-edge loading to failure is an appropriate measure of load bearing strength for rigid pipe but not for flexible pipe. When considering the load carrying capability of flexible pipe, the soil stiffness must be considered as well as the pipe stiffness.

EQUATION 1[3]

$$PS = F/\Delta Y \geq \frac{EI}{0.149r^3} = 0.559\ E \left(\frac{t}{r}\right)^3$$

Where:
- **PS** = Pipe stiffness, lbs/linear in./in or psi
- **F** = Force, lbs/linear in.
- **ΔY** = Vertical deflection, in.
- **E** = Modulus of tensile elasticity, psi
- **I** = Moment of inertia of the wall cross-section per unit length of pipe, in^4/linear in = in^3
- **r** = Mean radius of pipe, in.
- **t** = Wall thickness, in.

For solid-wall PVC pipe with outside-diameter controlled dimensions (rather than I.D.), Equation 1 can be further simplified:

EQUATION 2[3]

$$PS = 4.47 \left(\frac{E}{(DR - 1)^3}\right)$$

Note: This equation does not apply to profile wall pipes.

Where:
- **E** = Modulus of tensile elasticity, psi
- **DR** = Dimension ratio = $\frac{OD}{t}$
- **OD** = Outside diameter, in.
- **t** = Minimum wall thickness, in.

TABLE 1
PVC PIPE STIFFNESS (psi)

DR or SDR	Min. E = 400,000 psi	Min. E = 500,000 psi
51	14	18
42	26	32
41	28	35
35	46	57
33.5	52	65
32.5	57	71
28	91	114
26	115	144
25	129	161
21	234	292
18	364	455
17	437	546
14	815	1,019
13.5	916	1,145

The resulting minimum pipe stiffness (PS) values for PVC pipe with different dimension ratios are provided in Table 1.[3]

In addition to altering the "I" value by changing the DR, alternative shapes can be employed. It is this option of more efficient shapes that has resulted in a variety of profile-wall gravity PVC pipe products for sanitary and drain applications. Users are afforded the economy of a higher stiffness than a DR product of the same raw material quantity and strength.

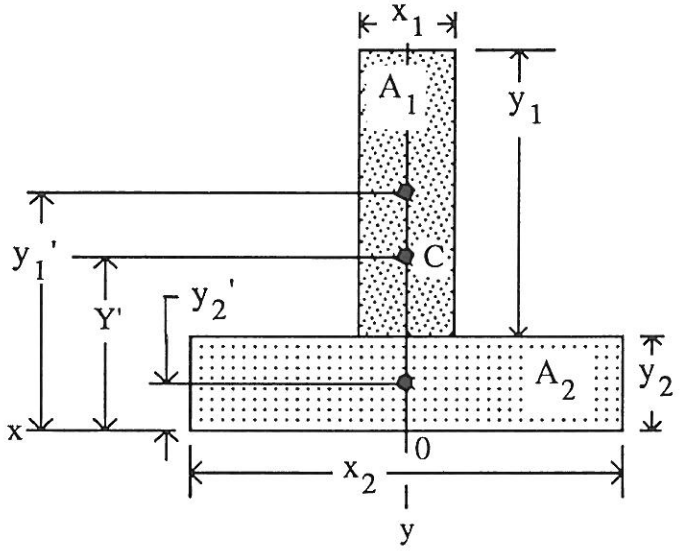
Equation 1 shows that the pipe stiffness increases as the moment of inertia of the wall cross-section increases. For a solid wall pipe, the moment of inertia is equal to $t^3/12$ $in^4/Lin.$, with the center of gravity being at the mid-point of the pipe wall.

In the case of a profile-wall pipe, however, the calculation of the moment iof inertia is more complex. First the center of gravity, or centroid, C must be calculated from a common x axis (the inside surface of the pipe) using Equation 3 (Figure 2).

EQUATION 3

$$Y' = \frac{\sum_i A_i y'_i}{\sum_i A_i}$$

FIGURE 2

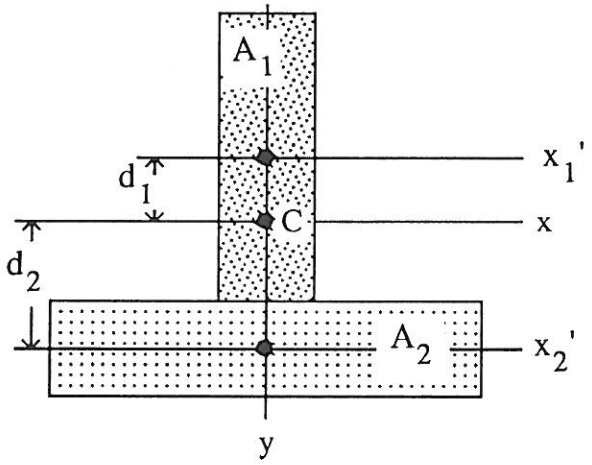


The moment of inertia is then determined as the sum of the moments for each component as determined by the parallel-axis theorem (Equation 4, Figure 3).

EQUATION 4

$$I_x = \sum_i (I'_{xi} + A_i d_i^2)$$

FIGURE 3

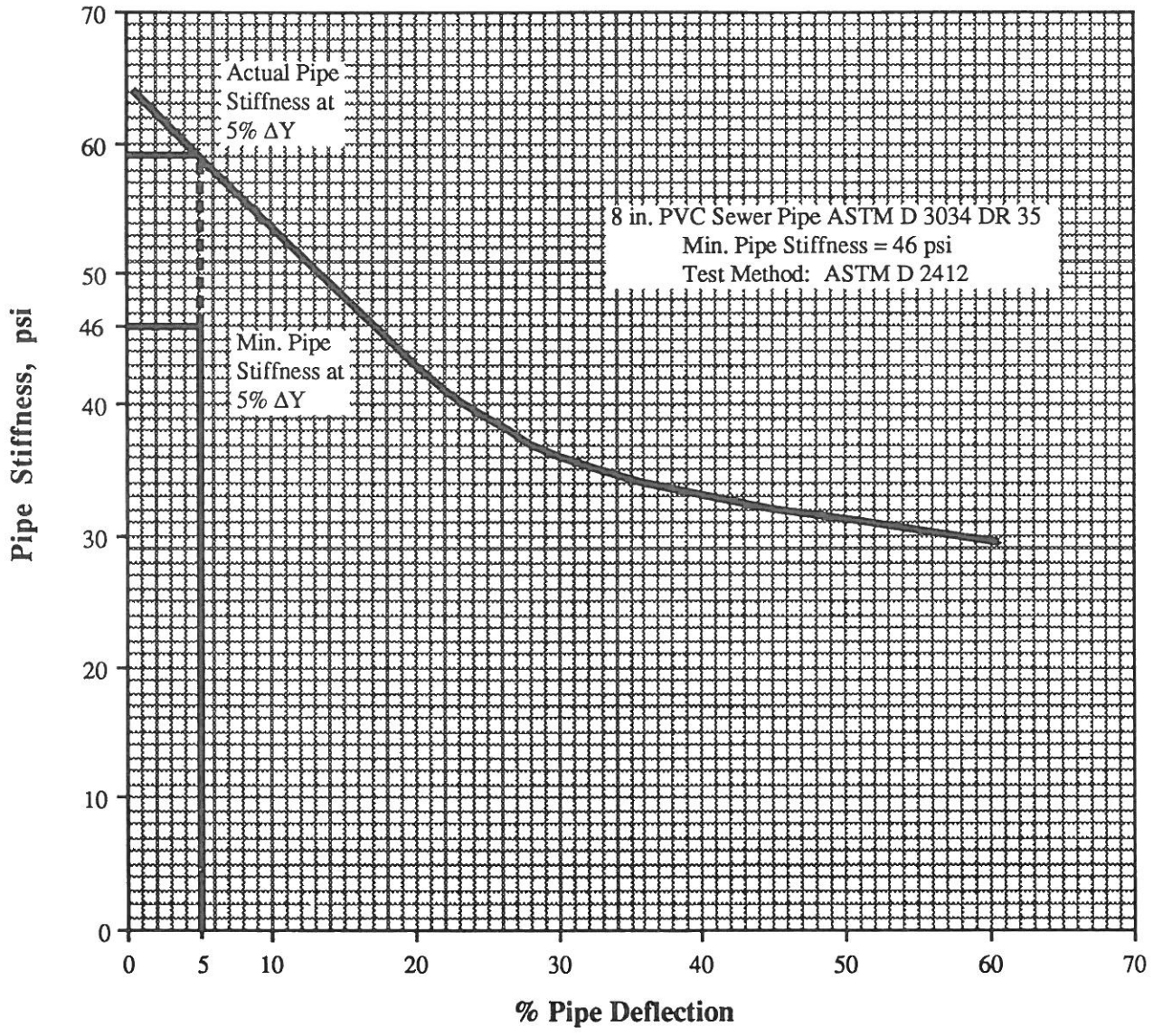


It is the location of the center of gravity in the pipe wall rather than its overall thickness that has the greatest effect on the moment of inertia and gives the profile wall pipes their high stiffness-to-weight ratios.

The arbitrary datum point of five percent deflection at which most pipe stiffness values are measured, was selected to permit meaningful comparison of pipe stiffness in different flexible pipes.[4] Pipe stiffness values for all flexible pipes will vary with deflection. A typical response of PVC sewer pipe to parallel plate loading is presented in Figure 4. Obviously, a standard datum point for measurement of pipe stiffness is required.

FIGURE 4

TYPICAL PIPE STIFFNESS TEST RESULTS
PIPE STIFFNESS VS. PERCENT DEFLECTION



Soil Stiffness. Soil Stiffness may be defined as the soil's ability to resist deflection.[9] Because of flexible pipe's ability to interact with the surrounding soil in supporting a given load, the soil stiffness is very important. Dr. Spangler further refined the measurement of soil stiffness by investigating "**e**", the Modulus of Passive Resistance. The modulus of passive resistance of side support soil is considered to be the unit pressure developed as the side of a flexible pipe moves outward against the side fill.[2] The "Modified Iowa Equation" was developed by Dr. M. G. Spangler and Dr. R. K. Watkins to permit calculation of the theoretical deflection of buried flexible conduits in terms of soil stiffness, regardless of pipe size.[2] The **E'** value is commonly termed the Modulus of Soil Reaction and is defined as the product of the modulus of passive soil resistance, **e**, and the mean pipe radius.

In field investigations, Dr. Spangler found **E'** values which ranged from a minimum of 234 psi in uncompacted clay loam to a maximum of 7980 psi in crushed sandstone soil which was compacted to Proctor density.[2] **E'** values for various soil conditions have been suggested by a number of scientists. On the basis of his observations, Dr. Spangler offered the general suggestion that a value of **E'** = 700 psi is recommended if the side support soil is compacted to 90 percent or more of Proctor density for a distance of two pipe diameters on each side of the flexible pipe.[2] He further advised that for lesser soil densities it should be anticipated that **E'** values will decrease rapidly. Amster K. Howard, of the U. S. Bureau of Reclamation, dedicated a substantial research effort to the investigation of average **E'** values for different types of soils and embedment materials at varying degrees of density.[11] The product of his research effort is presented in Table 2.

Earth Loads. Since 1913, loads imposed on buried conduits have been calculated by the Marston Load Formulas.[12] For trench loads, Professor Anson Marston, of Iowa State University, developed two formulas -- one for rigid and another for flexible pipe.[2] These load formulas are an integral part of the Marston Theory of Loads on Underground Conduits which is generally considered to be the "state of the art" in determination of loading on buried pipe. It is important to note that the dead load generated on a flexible conduit according to Marston is substantially less than the dead load generated on a rigid conduit under identical conditions in a narrow trench.[2] The ratio of the rigid load to flexible load is expressed as the trench width divided by pipe diameter. For example, if the trench width for a 12" pipe is 3 feet, the rigid pipe load, according to Marston will be 3 times that of the flexible pipe load.

TABLE 2

AVERAGE VALUES OF MODULUS OF SOIL REACTION, E'
(For Initial Flexible Pipe Deflection)

Soil type-pipe bedding material (Unified Classification System[a]) (1)	E' for Degree of Compaction of Pipe Zone Backfill, psi			
	Loose (2)	Slight <85% Proctor, <40% relative density (3)	Moderate 85%-95% Proctor, 40%-70% relative density (4)	High >95% Proctor, >70% relative density (5)
Fine-grained Soils (LL > 50)[b] Soils with medium to high plasticity CH, MH, CH-MH	No data available; consult a competent soils engineer; Otherwise use E' = 0			
Fine-grained Soils (LL < 50) Soils with medium to no plasticity CL, ML ML-CL, with less than 25% coarse-grained particles	50	200	400	1,000
Fine-grained Soils (LL < 50) Soils with medium to no plasticity CL, ML, ML-CL, with more than 25% coarse-grained particles Coarse-grained Soils with Fines GM, GC, SM, SC[c] contains more than 12% fines	100	400	1,000	2,000
Coarse-grained Soils with Little or No Fines GW, GP, SW, SP[c] contains less than 12% fines	200	1,000	2,000	3,000
Crushed Rock	1,000	3,000	3,000	3,000
Accuracy in Terms of Percentage Deflection[d]	±2	±2	±1	±0.5

[a]ASTM Designation D 2487, USBR Designation E-3.

[b]LL = Liquid limit.

[c]Or any borderline soil beginning with one of these symbols (i.e., GM-GC, GC-SC).

[d]For ±1% accuracy and predicted deflection of 3%, actual deflection would be between 2% and 4%.

Note: Values applicable only for fills less than 50 ft (15 m). Table does not include any safety factor. For use in predicting initial deflections only, appropriate Deflection Lag Factor must be applied for long-term deflections. If bedding falls on the borderline between two compaction categories, select lower E' value or average the two values. Percentage Proctor based on laboratory maximum dry density from test standards using about 12,500 ft-lb/cu ft (598,000 J/m^3) (ASTM D 698, AASHTO T-99, USBR Designation E-11). 1 psi = 6.9 kN/m^2.

SOURCE: "Soil Reaction for Buried Flexible Pipe," by Amster K. Howard, U.S. Bureau of Reclamation, Denver, Colorado. Reprinted with Permission from American Society of Civil Engineers Journal of Geotechnical Engineering Division, January 1977, pp. 33-43.

MARSTON'S LOAD FORMULAS[2]

EQUATION 5	EQUATION 6
Rigid	Flexible
$W_c = C_d w B_d B_d$	$W_c = C_d w B_d B_c$

Where:
- W_c = Load on conduit, lbs/linear ft.
- w = Unit weight of backfill, lbs/cu ft.
- B_c = Horizontal width of conduit, ft.
- B_d = Horizontal width of trench at top of conduit, ft.
- C_d = Load coefficient for conduits installed in trenches

In actual calculation of loads using Marston's equations, the term C_d must be determined for particular installation conditions. C_d is computed as follows:

EQUATION 7[12]

$$C_d = \frac{1 - e^{-2ku'H/B_d}}{2ku'}$$

Where:
- e = Natural logarithm base
- k = Rankine's ratio of lateral to vertical pressure
- u' = Coefficient of friction between backfill material and trench walls
- H = Fill height, ft.
- B_d = Trench width, ft.

Figure 5 is provided to simplify selection of values for the trench load coefficient, C_d.

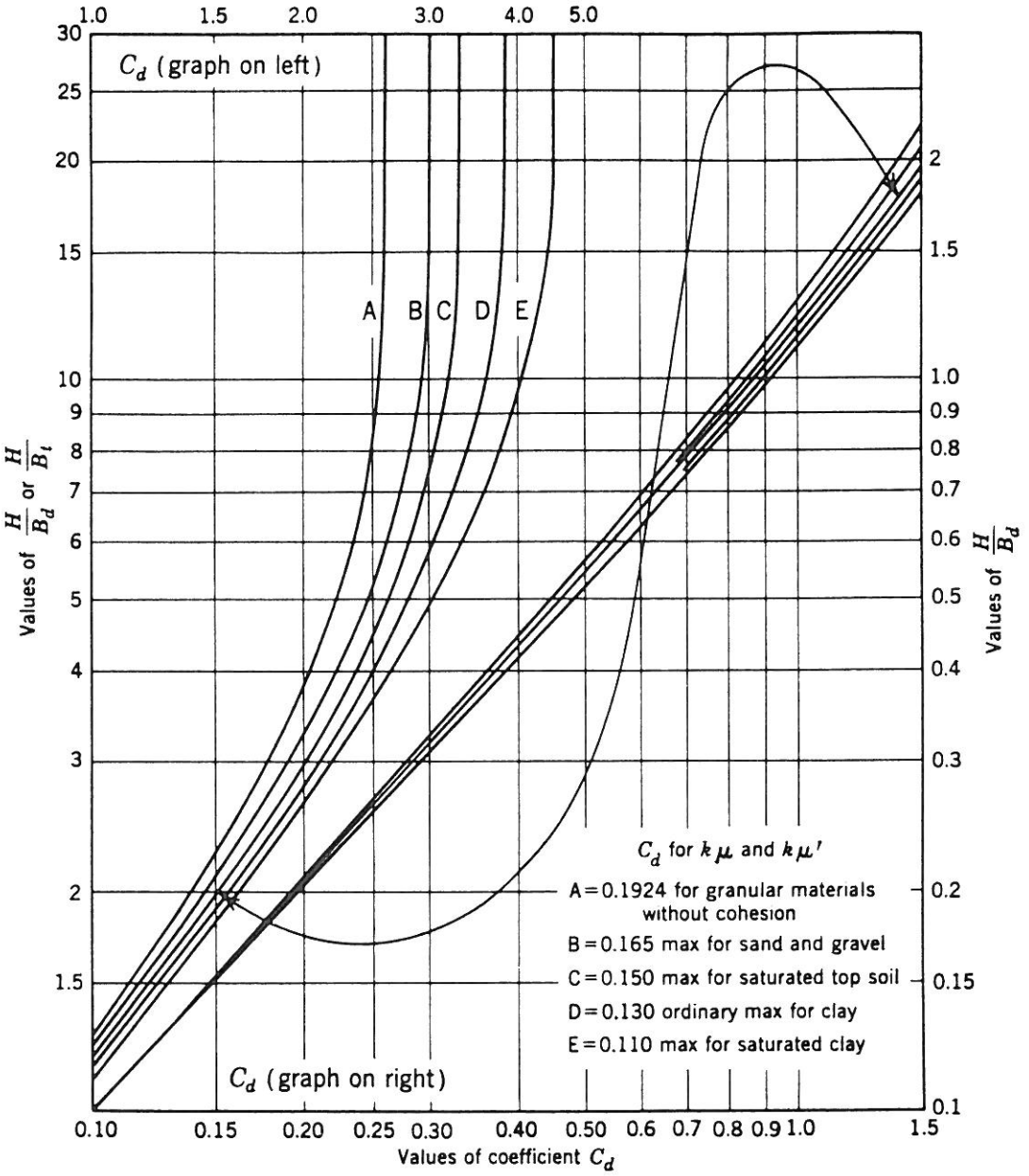
According to Marston, the width of the trench directly affects the load imposed on any buried pipe -- flexible or rigid.[2] An increasing width of trench does increase the load imposed on buried pipe; however, the load does not increase ad infinitum as the trench width increases. Beyond a certain width, termed the "transition width," for a given depth of burial and size of pipe, no additional load is imposed on a buried pipe.[12] The load realized by a buried pipe when trench width exceeds the transition width is properly termed the "embankment load." In general, the embankment load will be the maximum load which will be imposed by backfill overburden on a buried flexible pipe. The embankment load for flexible pipe is derived by determining the load imposed by the weight of the vertical prism of soil over the buried pipe, and is calculated as follows:

EQUATION 8[3]

$$W_c = HwB_c$$

Where:
- W_c = Load on conduit, lbs/linear ft
- w = Unit weight of backfill, lbs/ft^3
- B_c = Horizontal width of conduit, ft.

FIGURE 5
VALUES OF C_d



Computation diagram for earth loads on trench conduits (completely buried in trenches).

SOURCE: DESIGN & CONSTRUCTION OF SANITARY & STORM SEWERS, "MANUALS & REPORTS ON ENGINEERING PRACTICE NO. 37", AMERICAN SOCIETY OF CIVIL ENGINEERS AND "MANUAL OF PRACTICE NO. 9", WATER POLLUTION CONTROL FEDERATION, 1969, P. 189.

The more commonly used forms of the Modified Iowa Equation require that load on the pipe be expressed in pounds per square inch (psi). When expressed in this form, the prism load calculation is independent of pipe diameter as follows:

EQUATION 9

$$P = \frac{w H}{144}$$

Where: **P** = Prism load on conduit, psi
w = Unit weight of backfill, lbs/ft^3
H = Height of cover over the conduit, ft.

Dead load on buried flexible pipe should be calculated using the prism load equation providing conservative design unless the variables in the Marston flexible pipe equation can be determined with accuracy. It should be noted that the prism load as calculated using Equations 8 or 9 is not the maximum load which can be imposed on buried rigid pipe.[2]

For unknown conditions or in trenches with widths exceeding transition width, the more conservative embankment/prism loads are recommended as defined in Table 3. Prism earth loads presented in this table are expressed in pounds per square inch (psi) as required for use in the theoretical calculation of deflection. (Equations 12, 13 and 14, page 17.)

TABLE 3
PRISM LOAD (LBS/IN^2)

$$P = \frac{w H}{144}$$

Height of Cover (ft)	Soil Wt. (lbs/ft^3) 100	110	120	130	Height of Cover (ft)	Soil Wt. (lbs/ft^3) 100	110	120	130
1	0.69	0.76	0.83	0.90	16	11.11	12.22	13.33	14.44
2	1.39	1.53	1.67	1.81	17	11.81	12.97	14.17	15.35
3	2.08	2.29	2.50	2.71	18	12.50	13.75	15.00	16.25
4	2.78	3.06	3.33	3.61	19	13.19	14.51	15.83	17.15
5	3.47	3.82	4.17	4.51	20	13.89	15.28	16.67	18.06
6	4.17	4.58	5.00	5.42	21	14.58	16.04	17.50	18.96
7	4.86	5.35	5.83	6.32	22	15.28	16.81	18.33	19.86
8	5.56	6.11	6.67	7.22	23	15.97	17.57	19.17	20.76
9	6.25	6.88	7.50	8.13	24	16.67	18.33	20.00	21.67
10	6.94	7.64	8.33	9.03	25	17.36	19.10	20.83	22.57
11	7.64	8.40	9.17	9.93	26	18.06	19.86	21.67	23.47
12	8.33	9.17	10.00	10.83	27	18.75	20.63	22.50	24.38
13	9.03	9.93	10.83	11.74	28	19.44	21.39	23.33	25.28
14	9.72	10.69	11.67	12.64	29	20.14	22.15	24.17	26.18
15	10.42	11.46	12.50	13.54	30	20.83	22.92	25.00	27.08

Live Loads. Buried PVC pipe is also subject to live loads from traffic running over highways, railways or airport runways. Live loads have little effect on buried pipe performance except at

shallow depths of burial. The influence of live loads on the performance of PVC sewer pipe is only significant in shallow depths, usually less than four feet for highway loads,[3] see Table 4 (Live Loads on PVC Pipe). When considering influence of live loading from railroads, depths of burial less than 10 feet can permit significant live loads,[3] see Table 4.

TABLE 4

LIVE LOADS ON PVC PIPE

Height of Cover (ft)	Live Load Transferred to Pipe, lb/in²			Height of Cover (ft)	Live Load Transferred to Pipe, lb/in²		
	Highway H20[1]	Railway E80[2]	Airport [3]		Highway H20[1]	Railway E80[2]	Airport [3]
1	12.50			14	*	4.17	3.06
2	5.56	26.39	13.14	16	*	3.47	2.29
3	4.17	23.61	12.28	18	*	2.78	1.91
4	2.78	18.40	11.27	20	*	2.08	1.53
5	1.74	16.67	10.09	22	*	1.91	1.14
6	1.39	15.63	8.79	24	*	1.74	1.05
7	1.22	12.15	7.85	26	*	1.39	*
8	0.69	11.11	6.93	28	*	1.04	*
10	*	7.64	6.09	30	*	0.69	*
12	*	5.56	4.76	35	*	*	*
				40	*	*	*

[1] Simulates 20 ton truck traffic + impact.
[2] Simulates 80,000 lb/ft railway load + impact.
[3] 180,000 lbs. dual tandem gear assembly. 26 inch spacing between tires and 66 inch center-to-center spacing between fore and aft tires under a rigid pavement 12 inches thick + impact.
* Negligible live load influence.

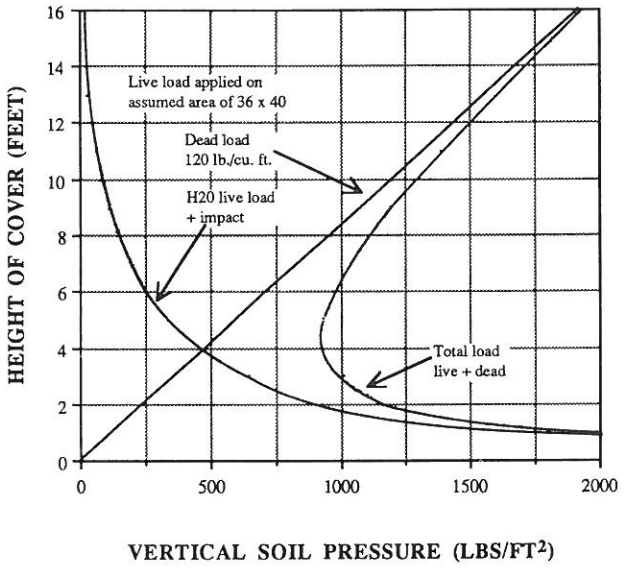
Figures 6 and 7 show live load, dead load and total load on buried pipe exposed to live loads and earth loads for highway and railway traffic. The H20 highway live load assumes two 16,000 pound concentrated loads applied to two 18" x 20" areas, one located over the point in question and the other located at a distance 72" away. The Cooper E-80 live load assumes 80,000 pounds applied to three 2' x 8' areas on 5' centers such as might be encountered through live loading from a locomotive with three 80,000 pound axle loads.

Figures 6 and 7 demonstrate clearly that as depth of cover increases over buried pipe, the live load and impact diminishes rapidly, especially when compared to the earth loading.

Having reviewed the primary factors which influence the performance of buried flexible pipe -- pipe stiffness, soil stiffness and load -- it is appropriate that the relationship of the three variables be summarized. In the performance of a buried flexible conduit (such as PVC sewer pipe) the vertical force vector derived from both earth load and live load will cause the conduit to deflect, thereby transmitting a substantial portion of the load to the side support soil.[8]

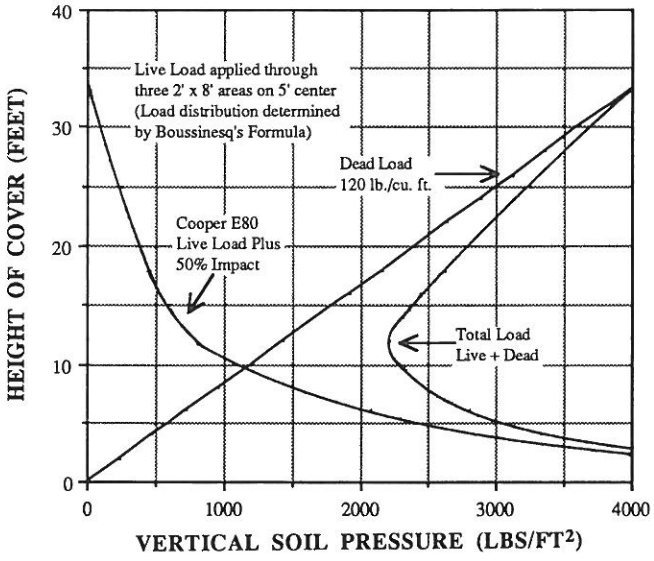
Therefore, the pipe stiffness and the soil stiffness in a combined system work to resist deflection, thereby providing opposite and equal reactions necessary to achieve equilibrium in the pipe/soil system which, in turn, assures stable, long-term performance of the buried flexible pipe.[6]

FIGURE 6
H20 HIGHWAY LOADING



SOURCE: AMERICAN IRON AND STEEL INSTITUTE, WASHINGTON, D.C.

FIGURE 7
COOPER E-80 LIVE LOADING



SOURCE: AMERICAN IRON AND STEEL INSTITUTE, WASHINGTON, D.C.

Deflection. It is readily apparent that deflection is essential to the proper performance of buried PVC sewer pipe. However, it is equally apparent that acceptable limits for deflection must be defined, and a means of projecting the anticipated deflection in a given installation is essential to proper PVC sewer piping system design.

Theoretical calculation of deflection in buried flexible pipe was researched in depth by Dr. M. G. Spangler, who decided that proper design of buried flexible piping systems required more than simple consideration of load. He published his Iowa Formula in 1941. The formula represented a major technological advance in theoretical prediction of deflection in buried flexible pipe. In 1955, Dr. Spangler and his student, Dr. R. K. Watkins, modified the original Iowa Equation to incorporate use of the Modulus of Soil Reaction (E'). The product of their labors, the Modified Iowa Equation, is generally considered the best acceptable theoretical method of predicting deflection in buried flexible pipe. The Modified Iowa Equation is stated:

EQUATION 10[2]

$$\Delta X = D_L \frac{K w_c r^3}{EI + 0.061\ E' r^3}$$

Where:
- ΔX = Horizontal deflection, in.
- D_L = Deflection lag factor
- K = Bedding constant
- W_c = Load per unit length of pipe, lbs/linear in.
- r = Mean pipe radius, in.
- E = Modulus of tensile elasticity of the pipe material, psi
- I = Moment of inertia per unit length, in.^{3}
- E' = Modulus of soil reaction, psi

The relationship between horizontal deflection (ΔX) and vertical deflection (ΔY) in buried flexible conduit was determined in the laboratory for pipe of various sizes at deflections under 10 percent by Dr. Spangler in the following equation:

EQUATION 11[2]

$$\Delta X = 0.913\ \Delta Y$$

Where:
- ΔX = Horizontal deflection, in.
- ΔY = Vertical deflection, in.

Under most soil conditions, flexible PVC pipe tends to deflect into a nearly elliptical shape and the horizontal and vertical deflections may be considered equal for small deflections (Δ). Since most PVC pipe is described by either pipe stiffness ($F/\Delta Y$) or outside diameter to thickness ratio (**DR**), the Modified Iowa Equation 10 can be transposed and rewritten as follows:

EQUATION 12

$$\% \text{ Deflection} = \% \frac{\Delta Y}{D} = \frac{D_L K P (100)}{0.149 \frac{F}{\Delta Y} + 0.061 E'}$$

EQUATION 13

$$\% \frac{\Delta Y}{D} = \frac{D_L K P (100)}{[2E/(3(DR - 1)^3)] + 0.061 E'}$$

Note: This equation does not apply to profile wall pipes.

Where: P = Prism load (soil pressure), psi

$P = \frac{wH}{144}$

w = Unit weight of soil, lb/ft^3

H = Height of cover over the pipe, ft.

Note that **P** must be in units of psi to work equations 12, 13 and 14.

When live loads such as H20 highway and E80 railway loadings must be considered, the following equation should be used:

EQUATION 14

$$\% \frac{\Delta Y}{D} = \frac{(D_L K P + K W')(100)}{[2E/(3(DR - 1)^3)] + 0.061 E'}$$

Where: P = Prism Load, psi

K = Bedding constant

W' = Live load, psi

DR = Dimension ratio

E = Modulus of tensile elasticity of the pipe material, psi

E' = Modulus of soil reaction, psi

D_L = Deflection lag factor

A brief review of the parameters used in the Modified Iowa Equation is appropriate.

The Deflection Lag Factor (D_L) accommodates the fact that in pipe/soil systems, as with all engineered structures involving soil, the soil consolidation at the sides of the pipe continues at an ever decreasing rate with time after the maximum load reaches the buried pipe, analogous to the time/settlement of soil under the load of a building foundation.[2] Experience demonstrates that deflection of buried flexible pipe will continue for a period of time after completion of pipe

installation before final equilibrium is achieved. A conservative value of 1.5 is frequently used for $\mathbf{D_L}$ in the Modified Iowa Equation (Eq. 10, page 16) when load on the pipe (**Wc**) is calculated using the Marston Load Formula (Eq. 6, page 11).

The full load on any buried pipe is not reached immediately after installation unless the final backfill is compacted to a high density. For a pipe with good flexibility, the long-term load will not exceed the prism load. The increase in load with time is the largest contribution to increasing deflection. Therefore, for design, the prism load can be used to compensate for the increased trench consolidation load with time and resulting increased deflection. When deflection calculations are based on prism loads, the deflection lag factor ($\mathbf{D_L}$), should be 1.0.

The Bedding Constant (**K**) accommodates the response of the buried flexible pipe to the opposite and equal reaction to the load force derived from the bedding under the pipe. The Bedding Constant varies with the width and angle of the bedding achieved in the installation. The bedding angle (θ) is shown in Figure 8.

FIGURE 8
BEDDING ANGLE

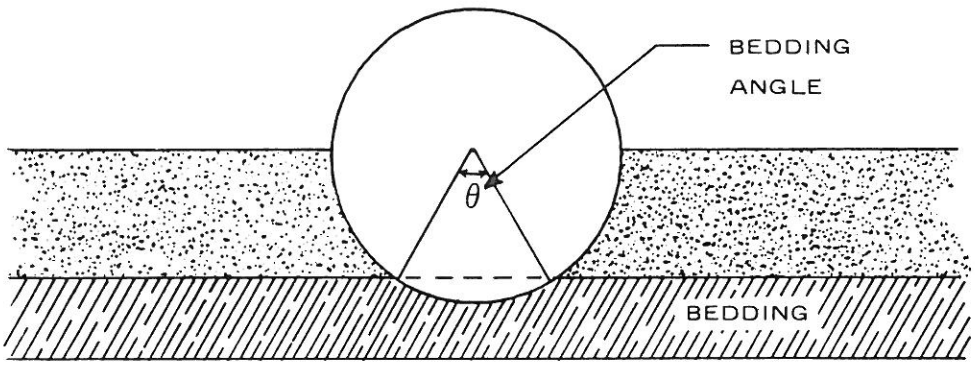


Table 5 presents a list of Bedding Constant values dependent on the bedding angle. As a general rule, when using the Modified Iowa Equation a value of $\mathbf{K} = 0.1$ is assumed.

TABLE 5
VALUES OF BEDDING CONSTANT, K

Bedding Angle (Degrees)	K
0	0.110
30	0.108
45	0.105
60	0.102
90	0.096
120	0.090
180	0.083

For years research scientists have struggled with the problem of measuring the Modulus of Soil Reaction (**E'**). In the effort to define E' values for different types of embedments, success has been somewhat limited in that evaluation of **E'** in given installations requires assumption of values for W_c, **K** and D_L. Extensive research by Amster K. Howard was conducted to determine average values of **E'** as shown in Table 2. Amster Howard obtained much of his research results from a laboratory cell with substantial accuracy; however, he also had to assume values for other constants in the Modified Iowa Equation.[11] Nevertheless, the data presented in Table 2 can be considered conservative and appropriate for use in the theoretical calculation of deflection since it is based on over one hundred well-documented field installations with many types of flexible pipe materials, pipe stiffnesses, deflections and embedment materials.

The theoretical method of calculating anticipated deflection of buried flexible pipe is encumbered by severe limitations in that it requires experimental investigation to determine the unknown constants with reasonable accuracy. Through the efforts of scientists in recent years, techniques have evolved whereby a model or prototype flexible pipe is tested until failure occurs, and in the course of testing, the total performance of the pipe is studied under a vast variety of conditions.

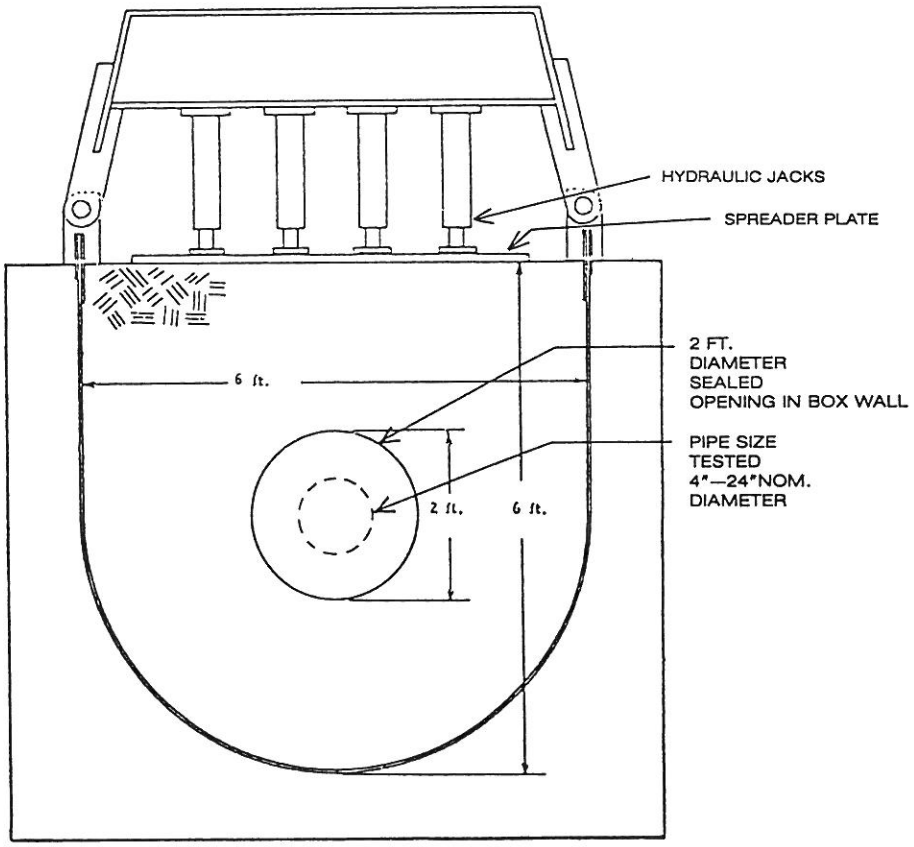
Such testing is commonly performed in soil cells where the flexible pipe is placed in the desired embedment materials and tested by applying a desired load on the top of the embedment material using hydraulic rams. Such testing is done with care taken to insure adequate distance between the test pipe and the rigid walls of the soil cell. The load applied to flexible pipe in such a test apparatus is essentially equivalent to a prism or embankment load and, therefore, accurately approximates the maximum load which can be realized by flexible pipe at a given depth of burial.[6] Using soil cells, the maximum, long-term deflection can be accurately measured for different loads calculated to represent different depths of burial.[7]

Laboratory testing using soil cell apparatus has been done extensively with great success at Utah State University under the direction of Dr. R. K. Watkins and others and at the United States Bureau of Reclamation under the direction of Amster K. Howard. Similar testing programs using

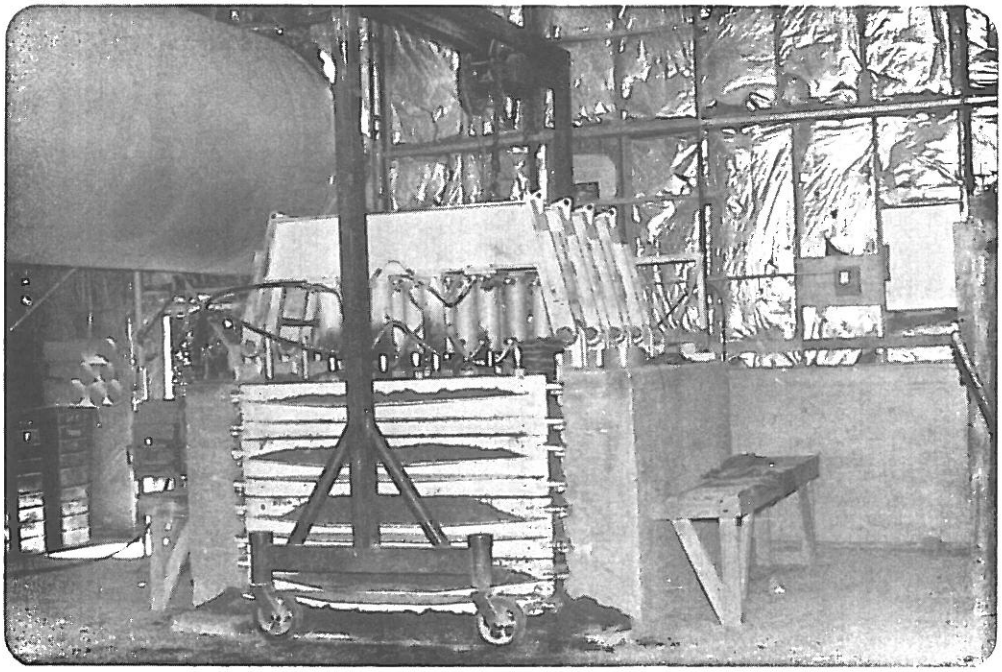
soil cells have been executed in other laboratories throughout the world. Data obtained from such research testing can be used directly in the design of flexible pipe/soil systems and in the prediction of overall performance. The possibilities of buckling, over-deflection and wall crushing are all evaluated simultaneously by actual tests. It is not necessary to analyze or explain the pipe/soil interaction phenomenon in the use of this test method; the end results leave nothing to be estimated on the basis of judgment.[8] A typical soil cell is described in Figure 9. Through such laboratory testing, PVC sewer pipe has been carefully evaluated to develop reliable empirical design data, thereby eliminating the reliance on theoretical calculations for design.

Extensive research has been conducted under the direction of Dr. Watkins and Dr. A. P. Moser at Utah State University to develop empirical design data for PVC sewer pipe. Their work has been corroborated by extensive field investigation and analysis of the performance of buried PVC sewer pipe systems.

FIGURE 9
SOIL CELL



SOURCE: UTAH STATE UNIVERSITY



A soil cell at Utah State University.

The product of the Utah State University research and field evaluations is presented in Table 6. The table presents the maximum long-term deflections predicted for PVC sewer pipe having a minimum pipe stiffness of 46 psi. The deflection data provided in the table represents the results obtained in both actual laboratory tests and field evaluations.[8] It should be noted that the predicted deflection values in the table depend on the following variables:

- Type of soil embedment
- Percent of Proctor Density (AASHTO T-99) in the pipe zone
- Height of Soil Cover

Since the deflection values presented represent maximum long-term data, a deflection lag factor need not be considered. Deflections realized in the trench in the conditions defined should not exceed the deflection values presented. Since the embankment load or prism load is used in the testing, the design data presented has been based on the maximum load which can be anticipated at the specified depths of burial. When considering the embankment load, the pipe diameter and trench width are not required; consequently, the table does not list these dimensions. Other values such as the Bedding Constant are also not defined in that empirical design data does not require consideration of such factors.

TABLE 6 - MAXIMUM LONG-TERM DEFLECTIONS OF PVC (SDR 35 OR PS 46) PIPE (PERCENT)

ASTM EMBEDMENT MATERIAL CLASSIFICATION		DENSITY (PROCTOR) AASTHO T-99	HEIGHT OF COVER (FEET)													
			3	5	8	10	12	14	16	18	20	22	24	26	28	30
Manufactured Granular Angular	CLASS I		0.2	0.3	0.4	0.5	0.6	0.7	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6
Clean Sand & Gravel	CLASS II	90%	0.2	0.3	0.5	0.7	0.8	0.9	1.1	1.2	1.3	1.4	1.6	1.7	1.8	2.0
		80%	0.9	1.4	2.3	3.2	3.6	4.1	5.0	5.5	6.0	6.4	7.3	7.7	8.2	9.1
Sand & Gravel with Fines	CLASS III	90%	0.2	0.4	0.6	0.8	0.9	1.1	1.2	1.4	1.6	1.7	1.9	2.1	2.2	2.3
		85%	0.7	0.9	1.7	2.2	2.6	3.0	3.5	3.9	4.3	4.8	5.2	5.6	6.0	6.5
		75%	1.1	1.8	2.9	3.8	4.5	5.5	6.8	8.5	9.9	11.3	12.7	14.1	15.5	16.8
Silt & Clay	CLASS IV	85%	0.65	0.9	1.7	2.2	2.6	3.0	3.5	3.9	4.3	4.8	5.2	5.6	6.0	6.5
		75%	1.3	2.3	3.3	4.3	5.0	6.5	7.8	9.5	10.6	12.2	13.5	15.0	16.3	17.0
Organic Soils & Peat	CLASS V	THIS SOIL CLASS NOT RECOMMENDED														

THESE ZONES NOT RECOMMENDED.

1. No length of pipe installed under conditions specified will deflect more than is indicated; the pipe will deflect less than the amount indicated if specified density is obtained.
2. Embedment material classifications are per ASTM designation D 2321-89, "Underground Installation of Thermoplastic Pipe for Sewers and Other Gravity-Flow Applications."
3. Deflections listed in table are maximum long-term values. Recommended deflection test limit is 7.5 percent.
4. Listed deflections are those caused by soil loading only and do not include initial out of roundness, etc.

NOTE: Installations in excess of 30 feet are possible and have been successfully completed.

Data presented in this manner is designed to provide a great deal of convenience to engineers. Its use in most cases will demonstrate that several engineering solutions may be available, and economic inputs may suggest a proper solution. For example, suppose PVC sewer pipe with a minimum pipe stiffness of 46 psi is to be installed where the native soil is a Class IV clay. Ninety percent of the line will be at depths as great as 20 feet. According to Table 6, the native Class IV material could be used for embedment of that portion of the pipeline with less than 14 feet of cover if compacted to 75 percent of Standard Proctor, thereby projecting maximum deflection less than 7.5 percent. However, ground water conditions may make compaction difficult, even impossible, or may result in subsequent reduction in soil strength. If this is the case, Class II (fine) or III material may be imported and used with appropriate embedment procedures to limit deflection to 7.5 percent. The choice will be based on availability, convenience and, ultimately, on cost. For the deep portion of the line, Class III material compacted to 85 percent, Class II material compacted to 80 percent or Class I material without compaction could be used successfully. It should be noted that when imported materials are used in aggressive subsurface water table environments, the design should preclude native fines from washing into these materials. If imported material must be used in these areas, it should be well graded. See Table 7 for description of embedment material classifications.

Having reviewed flexible conduit theory as it relates to both the theoretical and empirical prediction of deflection, it becomes obvious that long-term deflection of buried PVC sewer pipe can be predicted with acceptable accuracy.

TABLE 7 - DESCRIPTION OF MATERIAL CLASSIFICATION

Class	Type	Soil Group Symbol	Description ASTM D 2487	Percentage Passing Sieve Sizes 1.5 in (40 mm)	No. 4 (4.75 mm)	No. 200 (0.075 mm)	Atterberg Limits LL	PI	Coefficients Uniformity C_u	Curvature C_c
IA	Manufactured Aggregates: open-graded, clean.	None	Angular, crushed stone or rock, crushed gravel broken coral, crushed slag, cinders or shells; large void content, contain little or no fines	100%	≤10%	<5%	Non Plastic			
IB	Manufactured, Processed Aggregates; dense-graded, clean.	None	Angular, crushed stone (or other Class IA materials) and stone/sand mixtures with gradations selected to minimize migration of adjacent soils; contain little or no fines	100%	≤50%	<5%	Non Plastic			
II	Coarse-Grained Soils, clean	GW	Well-graded gravels and gravel-sand mixtures; little or no fines	100%	<50% of Coarse Fraction	<5%	Non Plastic		>4	1 to 3
		GP	Poorly-graded gravels and gravel-sand mixtures; little or no fines						<4	<1 or >3
		SW	Well-graded sands and gravelly sands; little or no fines		>50% of Coarse Fraction				>6	1 to 3
		SP	Poorly-graded sands and gravelly sands; little or no fines						<6	<1 or >3
	Coarse-Grained Soils, borderline clean to w/fines	e.g. GW-GC, SP-SM.	Sands and gravels which are border-line between clean and with fines	100%	Vanes	5% to 12%	Non Plastic		Same as for GW, GP, SW and SP	
III	Coarse-Grained Soils With Fines	GM	Silty gravels, gravel-sand-silt mixtures	100%	<50% of Coarse Fraction	>12% to <50%		<4 or <"A" Line		
		GC	Clayey gravels, gravel-sand-clay mixtures					<7 and >"A" Line		
		SM	Silty sands, sand-silt mixtures		>50% of Coarse Fraction			>4 or <"A" Line		
		SC	Clayey sands, sand-clay mixtures					>7 and >"A" Line		
IVA[A]	Fine-Grained Soils (inorganic)	ML	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands, silts with slight plasticity	100%	100%	>50%	<50	<4 or <"A" Line		
		CL	Inorganic clays of low to medium plasticity, gravely clays, sandy clays, silty clays, lean clays					>7 and >"A" Line		
IVB	Fine-Grained Soils (inorganic)	MH	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts	100%	100%	>50%	>50	<"A" Line		
		CH	Inorganic clays of high plasticity, fat clays					>"A" Line		
V	Organic Soils	OL	Organic silts and organic silty clays of low plasticity	100%	100%	>50%	<50	<4 or <"A" Line		
		OH	Organic clays of medium to high plasticity, organic silts				>50	<"A" Line		
	Highly Organic	PT	Peat and other high organic soils							

[A]Includes Test Method ASTM D 2487 borderline classifications and dual symbols depending on plasticity index and liquid limits.
NOTE: "Coarse Fraction" as used in this table is defined as material retained on a No. 200 sieve.

PERFORMANCE LIMITS - FACTS AND MYTHS

In any engineering design, the performance limits of the material under consideration must be known in order for the design basis to be chosen. The particular application will dictate which of the material's performance limits is critical. This limit will then govern the design.

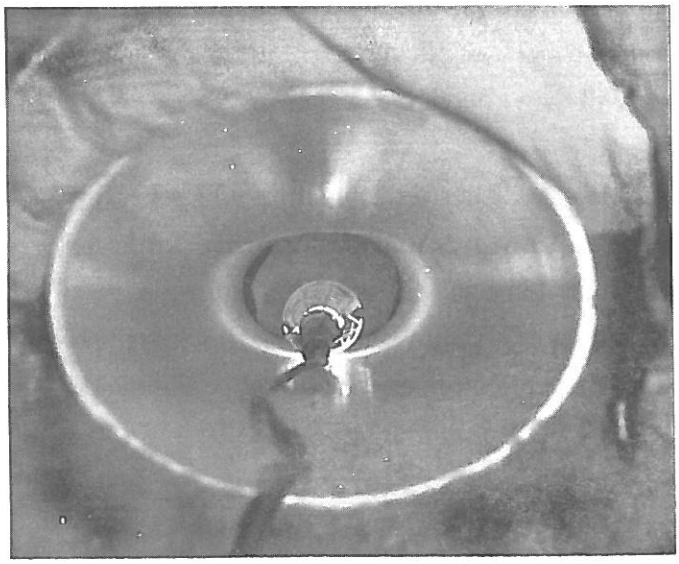
For PVC pipe used in gravity flow sewer applications the critical performance limit will generally be deflection. It is appropriate that we analyze the various potential performance limits to determine their relationship to deflection and design. Such items as wall structure, strain, fatigue, flow capacity, future maintenance, joint integrity, slope integrity, future connections, buckling and acceptance testing must each be considered in establishing deflection as the critical performance limit.

Deflection. The American Society for Testing and Materials (ASTM) recommends that the maximum deflection test limit for buried PVC sewer pipe should be 7.5 percent of the base inside diameter of the pipe.[10] The development of this recommendation could not be possible without establishing the critical performance limit for PVC sewer pipe in deflection. Before offering a recommendation for a test deflection limit, the manner in which PVC sewer pipe will perform in deflection must be defined. The deflection limit at which PVC sewer pipe ceases to function as a structurally sound buried conduit can be defined as the critical performance limit. Having established the critical performance limit, the exercise of developing a recommended design deflection limit then simply requires selection of a desired factor of safety. The critical performance deflection limit is then divided by the safety factor to provide the desired recommendation for design deflection limit.

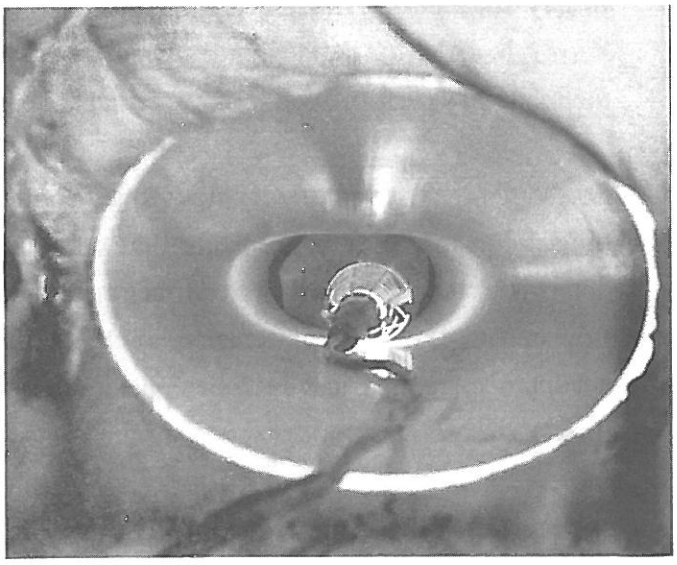
Research was conducted at Utah State University,[19] on PVC pipe having a minimum pipe stiffness of 46 psi, to determine the percent deflection which would limit the structural performance of the pipe. An embankment load was placed on the pipe via a soil cell (see Figure 9). Load and deflection measurements were taken and pipe wall performance was continuously observed.

The photos in Figure 10 reveal the sequence of events during loading of the PVC pipe. Because high deflections were required to evaluate structural performance, the pipe was embedded in slightly compacted material.

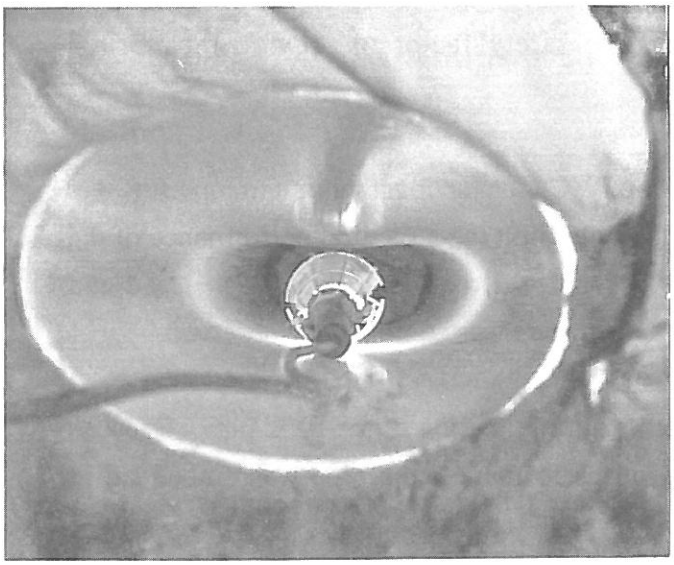
FIGURE 10



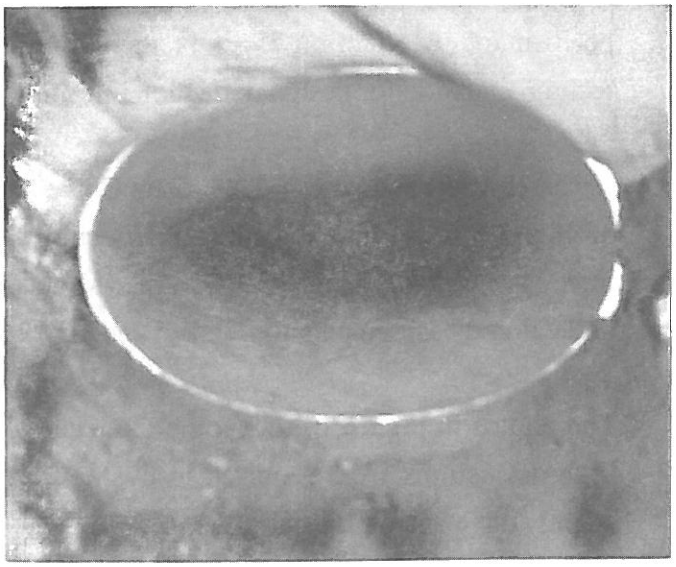
10A
28.3% Vertical Deflection
Load Approximately 10,600 lbs/sq.ft.



10B
39.6% Vertical Deflection
Load approximately 15,800 lbs/sq.ft.



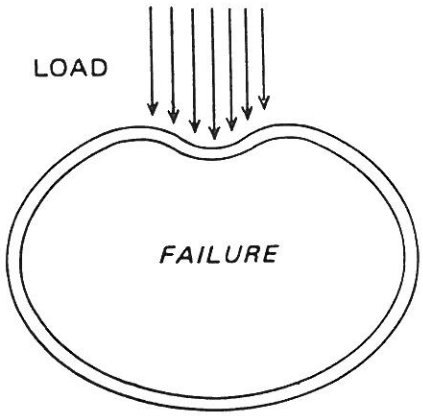
10C
49.5% Vertical Deflection
Load approximately 20,600 lbs/sq.ft.



10D
57.8% Vertical Deflection
Load in Excess of 22,500 lbs/sq.ft.

This research revealed that the critical limit is established as the result of a phenomenon called inverse curvature (See Figure 11). If this limit is surpassed in a buried flexible conduit, inverse curvature in the upper portion of the pipe circumference can occur.

FIGURE 11
INVERSE CURVATURE CAUSED BY EXCESSIVE DEFLECTION



Loss of elliptical profile; the pipe can no longer effectively transfer load to side support soil.

This phenomenon in a buried flexible pipe can be considered failure in that the interrelation between the pipe stiffness and the soil stiffness is compromised. Equilibrium derived through a proper function of a flexible pipe is lost. The data indicates that while there is no catastrophic structural failure, and the pipe continues to support the load, the ability to transfer load to the side support soil is decreased once inverse curvature begins.

Figure 10a clearly reveals that inverse curvature has not yet begun at 28.3 percent. However, inverse curvature is evident in 10b at 39.6 percent. Even though the embedment material was slightly compacted, it took extremely high loads to produce these deflections. Using a unit weight of soil of 120 lbs/cu.ft., the equivalent depth of cover required to produce the deflections in Figures 10a and 10b were 88 and 131 feet, respectively.

What is perhaps more significant than this is the increased load it took to get the increase in deflection from 28.3 percent to 39.6 percent. An increase of approximately 5,000 lbs/sq.ft. was required to increase deflection by 11 percent.

Additional load was required to continue deflecting the pipe once inverse curvature began, which was observed at approximately 30 percent. This research clearly revealed that the structural

integrity of PVC pipe, with a minimum pipe stiffness of 46 psi, is maintained at deflections of 30 percent or less. It also revealed that at deflections in excess of 30 percent, additional load is required to increase deflection, but the ability to shift the load to the side columns of soil is decreased. Therefore, the critical deflection limit is 30 percent.

Selection of safety factors is essentially an arbitrary decision. A *4:1* factor of safety is selected in an effort to provide an extremely conservative recommendation for test deflection limits. The recommended allowable test deflection of 7.5 percent is arrived at by dividing 30 by 4.

Wall Structural Failure. PVC sewer pipe meeting ASTM product and performance standards must satisfy a series of quality control tests and inspection requirements. A significant test requirement in many of these standards states that "there shall be no evidence of splitting, cracking or breaking" when the pipe is subjected to the Flattening Test.[10] In this test, as a routine quality control requirement during manufacturing, samples of PVC sewer pipe are placed between parallel plates in a suitable press and flattened "until the distance between the plates is 40 percent of the outside diameter of the pipe."[10] The samples are then removed from the test apparatus and inspected for evidence of failure. Of course, in this test the PVC sewer pipe is subjected to a 60 percent deflection and must not display any signs of structural failure.

It is obvious that wall structural failure is not the critical failure mode which will establish the deflection failure limit for PVC sewer pipe. It must be emphasized that the term, "flexible pipe," is applicable to a broad range of products. Although structural failure does not dictate deflection limits for PVC sewer pipe, it should be considered the critical failure mode for some other flexible pipe products. Each flexible pipe product must be evaluated on its own merits, and design recommendations must consider the specific benefits and limitations, such as the critical structural failure mode, afforded by that product.

Strain. Strain is generally not a performance limiting factor for buried PVC pipe. Total strain in a pipe wall can be caused by two actions: (1) flexure of the pipe as it deforms and (2) hoop stress in the pipe wall. Determination of strains due to hoop stress is straight forward. If a homogeneous wall is assumed and pressure concentrations are neglected, the formula follows:

EQUATION 15

$$\epsilon_h = \frac{PD}{2tE}$$

Where: ϵ_h = Maximum strain in the pipe wall due to hoop stress, in/in.
P = Pressure on pipe (may be internal and/or external pressure with the appropriate sign), psi
E = Modulus of elasticity of the pipe material, psi
t = Pipe wall thickness, in.
D = Pipe diameter, in.

Maximum strains due to ring deflection or flexure may be determined by assuming the pipe remains an ellipse during deflections. The resulting equation is:

EQUATION 16

$$\epsilon_f = \frac{t}{D}\left[\frac{3\Delta Y/D}{1 - 2\Delta Y/D}\right] = \frac{1}{DR}\left[\frac{3\Delta Y}{D - 2\Delta Y}\right]$$

Where: ϵ_f = Maximum strain in pipe wall due to ring deflection or flexure, in/in.
ΔY = Vertical decrease in diameter, in.
t = Pipe wall thickness, in.
D = Pipe diameter, in.
DR = Dimension ratio

In a buried pipeline these strain components act simultaneously. The maximum combined strain in the pipe wall can be determined by summing both components.

EQUATION 17

$$\epsilon = \epsilon_f + \epsilon_h$$

Where: ϵ = Maximum combined strain in pipe wall in/in.

PVC pipe is more tolerant of compression strains than tension strains. Excessive tension strain can cause PVC pipe to crack. In calculating the maximum combined strain, hoop tension strains resulting from the applied internal pressure, if any, should be added to the maximum flexure strain in the pipe wall due to ring deflection. Conversely, ring compression strains from external soil loads should be subtracted to obtain the maximum combined strain.

On the basis of extensive investigations of PVC sewer pipes subjected to constant strain caused by deflection, it was found that the strain in the pipe material caused by deflections up to 20 percent

could not give rise to failure within a 50 year period. Refer to papers by Janson and Molin, Janson, Moser and Jensen (reference numbers 15, 16, 17 and 18). In the Janson investigation, 16 samples of PVC sewer pipe were deflected as much as 25 percent, corresponding to a relative strain in the pipe wall of 0.025 in/in. (2.5 percent). None of the 16 pipe samples, which were stored both in water and in a mixture of water and 2 percent detergent, showed any failures or cracks after a loading exposure time of more than 10 years.

In the Moser investigation, strips of PVC obtained from PVC pipe in either the longitudinal direction or the circumferential direction were tested under severe uniform strain conditions which are more critical than the bending strain associated with deflected buried pipe. After more than three years of observation, there is no indication that any of the circumferential samples that were strained to 5, 10, 20, 30 or 40 percent will fail in the future. The longitudinal specimens were able to withstand constant strains approaching 100 percent. Thus, strain is not a design limiting criterion for PVC pipelines.

Fatigue. The fatigue performance limit may be a consideration in both pressure and gravity flow pipe applications. However, most gravity flow sanitary systems function under conditions which do not warrant consideration of fatigue as a performance limit. PVC is similar to most materials in that it can fail at stresses lower than the strength of the material if a repeating stress application occurs at a sufficiently high frequency and magnitude on a continuous basis over a period of time. Cyclic stress variations can be induced internally by surge pressures and water hammer effects or the stress cycles can be caused from external loads such as traffic loadings on pipelines at shallow depths of burial.

The performance of PVC sewer pipe exposed to dynamic wheel loadings while buried at shallow burial depths has been evaluated at the Geotechnical Laboratory, U.S. Army Engineer Waterways Experiment Station. Figure 12 is typical of the results obtained from the evaluation. It was concluded that PVC (DR 35) pipe performed very well under a range of loadings representative of highway and light to medium aircraft traffic. A minimum cover height of 12 inches is recommended for PVC pipe, with a minimum pipe stiffness of 46 psi, subjected to highway loads of up to 18 kip axle. Under light to medium aircraft loads of up to 320,000 pounds gross weight, a minimum burial depth of 2 feet is recommended.

Figure 12 reveals that positive deflections may occur. During installation an increase in vertical diameter may result from excessive sidefill compaction.

It is recommended that special attention be given to the selection, placement and compaction of backfill material with shallow burial flexible pipe, such as PVC pipe underneath rigid pavement to prevent injurious cracking of the road surface.

Loss of Hydraulic Flow Capacity. All sanitary sewer systems are designed with serious attention given to flow capacities and velocities. It is a fact that flow capacity is affected by deflection in that the cross-sectional area of the pipe will be reduced with increased ovality. Of course, the engineer must base much of his design on the basic law of hydraulics, Q = AV. However, the extent to which deflection, within reasonable limits, will reduce the flow capacity must be evaluated. Table 8 shows the reduction in cross sectional area at varying vertical deflections.

FIGURE 12

PERMANENT DEFLECTION OF 12 IN. DR 35
PVC PIPE AS A FUNCTION OF TRAFFIC (CTT)

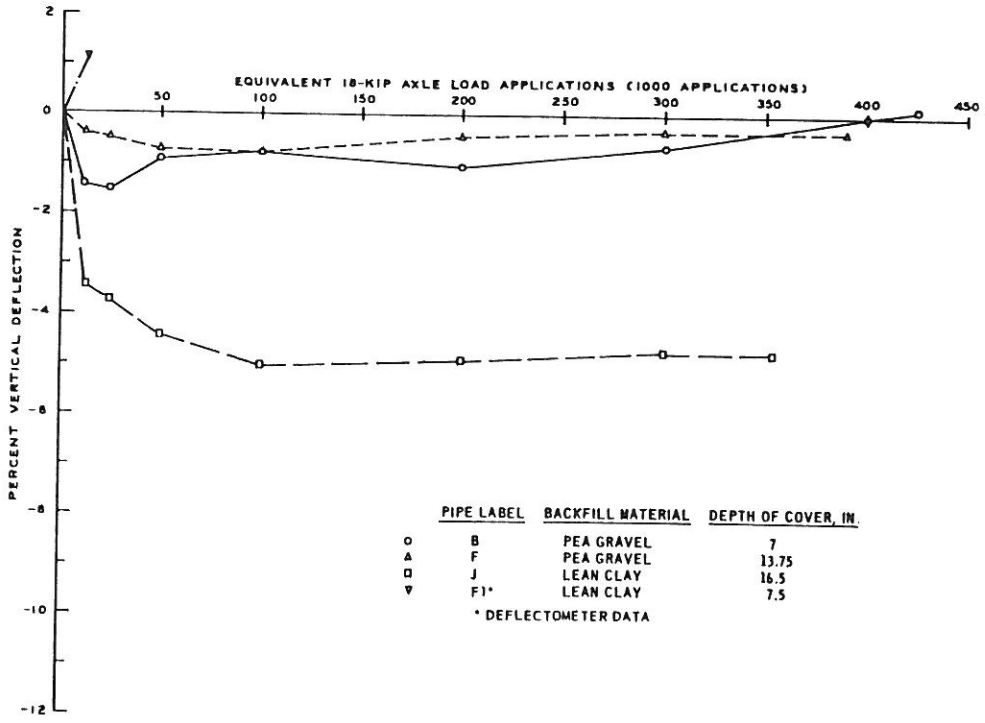


TABLE 8[3]

REDUCTION IN CIRCULAR CROSS-SECTIONAL AREA BY DEFLECTING FLEXIBLE PIPES

Deflection (%)	% Reduction in Internal Cross Sectional Area from Circular to Elliptical Shape
5	0.37
7.5	0.90
10	1.43
15	3.15
20	5.47
25	8.38
30	11.81
35	15.76

Recognizing the generous safety factors customarily used in the sizing of sanitary sewer systems, it becomes apparent that reduction in flow capacity due to deflections of 30 percent or less cannot be considered as critical to the performance of the conduit.

Impairment of Proper Cleaning. In general, PVC sewer pipe provides relatively few joints and smooth, non-wetting interior walls which render the product extremely well suited for effective cleaning with modern, high-pressure hydraulic cleaning equipment. Root intrusion into buried PVC sewer lines is essentially non-existent. The product's resistance to root penetration is generally attributed to the following properties:

- The PVC pipe wall is impervious and non-porous.
- The flexible PVC sewer pipe wall does not crack or break in service.
- Elastomeric gasket joints manufactured in accordance with UNI-B-1 and ASTM D 3212 effectively resist root intrusion.

It is obvious that mechanical cleaning tools such as root saws, augers, etc., are not required in the maintenance of PVC sewer lines. However, even when mechanical cleaning apparatus is used, the highly resilient nature of the PVC combined with its extremely high abrasion resistance precludes damage in the buried line. The cleaning of PVC sewer lines using pneumatically inflated "pigs" is accomplished without difficulty. If significant ovality in the sewer line is anticipated, a slight reduction in the inflation pressure (5 to 7 psi) of the "pig" will permit passage.

When evaluating the experience accumulated in maintenance and cleaning of PVC sewer pipe, a salient point becomes obvious. This Association has received no reports from the users of PVC sewer pipe in North America defining problems or failures caused by any cleaning devices -- either

mechanical or hydraulic. This impressive performance record speaks for itself. Therefore, it would be difficult, if not impossible, to justify limiting deflection to provide for effective cleaning.

Leakage in Deflected Joints. Concern has been expressed by some sanitary sewer system operators that PVC sewer pipe joints could leak if subjected to "excessive deflection." Research was conducted at the Utah State University Buried Structures Laboratory to evaluate the performance of integral bell gasket joints when deflected by severe earth loading conditions. The gasket joints tested were manufactured to meet the requirements of ASTM D 3212.

Tests were conducted on eight inch PVC sewer pipe, having a minimum pipe stiffness of 46 psi, with integral bell gasket joints. Test specimens were installed in sandy silt. Soil densities were measured using a nuclear density gauge. Tests were conducted in embedment soils placed with both 65 and 85 percent standard proctor density (AASHTO T-99). Specimens were tested under loads equivalent to buried depths greater than 35 feet. Abusive conditions were created by placing a ten pound rock on the male spigot end next to the bell joint. (See Figure 13.) Joints were tested with 3.5 psi air pressure held for five minutes. Results obtained in this research are summarized in Table 9.

Integral bell gasketed joints utilizing flexible elastomeric seals are ideal for use with PVC pipe. Such joints allow for differential deflection between the bell and spigot ends of deflected pipe without leakage. In fact, the bell end of the pipe combines with the inserted spigot end to form an extra strong joint that resists both leakage and deflection. The spigot end is shielded from the overburden by the stiffer bell end of the adjacent pipe section. The small difference between spigot outside diameter and bell end inside diameter effectively precludes differential deflections of a magnitude that could cause any excessive infiltration and/or exfiltration. Thus, infiltration limits can not be used as a basis for establishing a deflection limit.

FIGURE 13

ABUSIVE TEST CONDITION FOR PVC JOINT TEST IN SOIL CELL WITH TEN POUND ROCK ON SPIGOT END

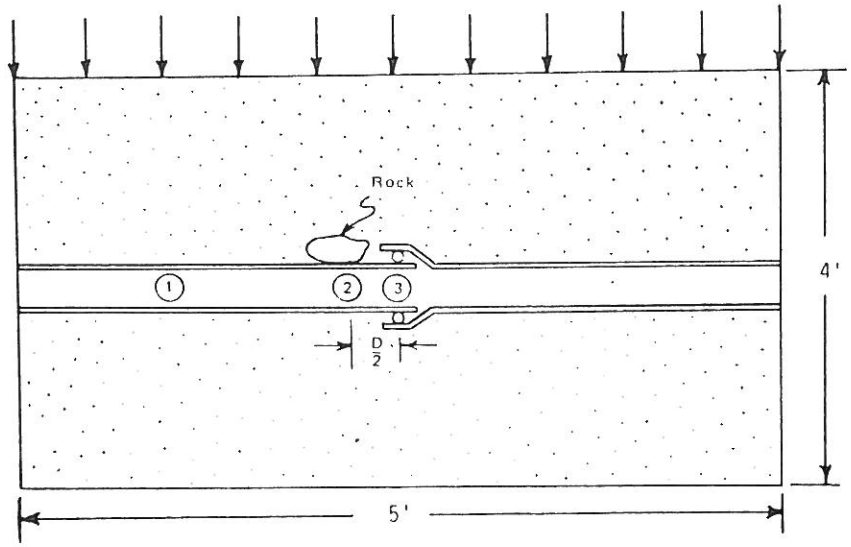


TABLE 9

RESULTS OF PVC JOINT TEST

Test No.	Test Description	Percent Deflection When Test Terminated			Comments[a]
		1	2	3	
1	85% soil density no rock	33		27	No leakage at 11,700 lb/ft^2 (H = 97 ft)
4	65% soil density no rock	30		25	No leakage at 5,840 lb/ft^2 (H = 48 ft)
		43			No leakage at 11,687 lb/ft^2 (H = 97 ft)
2	85% soil density with rock	33	43	32	No leakage at 11,700 lb/ft^2 (H = 97 ft)
3	65% soil density with rock	20	43	18	Joint leaked at 4,370 lb/ft^2 (H = 36 ft)

[a]Leakage test conducted with 3.5 psi air pressure held for five (5) minutes.

Loss of Line and Grade. No direct correlation exists between deflection and grade control, i.e., large deflections can occur without affecting proper grade, and low spots in grade can occur in the absence of large deflections. Thus, deflection testing does not provide for line and grade control. If concerned with line and grade control, the installer may wish to lamp the line after installation or use modern laser equipment now available. Such tests are easier to run than deflection tests and provide assurance of proper line and grade control for all types of sewer materials.

Impairment of Future Lateral Connections. The first step in making a service connection to a previously installed sewer line is to excavate down to the existing line, i.e., remove the overburden around the section of pipe to be tapped. PVC pipe has a property known as "elastic memory" which causes it to want to return to the shape in which it was originally formed. Consequently, as soon as the overburden is removed from a deflected PVC pipe, the pipe begins returning to its original round shape. Actual tests have confirmed this phenomenon. In addition, the modern saddles used with PVC pipe are at least as flexible as the pipe being tapped and sometimes are equipped with elastomeric seals, thus a saddle can easily be strapped to even a deflected pipe and achieve a good, watertight seal. Today's modern PVC pipe saddles are designed to flex with the pipe to which they are strapped. Even deflection occurring after installation will not diminish the integrity of the tap. A discussion with contractors who have utilized these modern taps will bear this out. The consideration of service taps on buried PVC sewer lines demonstrates negligible influence on selection of deflection limits.

Line Collapse. The critical mode of failure in a buried PVC sewer line involves realization of conditions which can either exceed the strength of the pipe/soil system or compromise the interrelation of the soil stiffness and pipe stiffness preventing the equilibrium which is essential to the strength of the pipe/soil system. In either instance, having realized such conditions, line collapse could be considered incipient.

We will first consider the condition where the combined strength of the pipe/soil system, although great, has been exceeded. This condition can be realized without excessive deflections. In conditions of internal vacuum, subaqueous installations or extremely loose soil burial, if the external load exceeds the compressive strength of the PVC pipe wall cross-section, buckling of the pipe wall can occur which will inevitably prevent proper long-term performance of the PVC sewer pipe. The pipe will cease functioning as an effective mechanism which can transfer vertical force vectors derived from load into approximately horizontal force vectors. See Figure 14.

For a circular ring subjected to uniform external pressure or internal vacuum, the critical buckling pressure (P_{cr}) is defined theoretically by Timoshenko as:[13]

EQUATION 18

$$P_{cr} = \frac{3EI}{r^3}$$

Where:
- P_{cr} = Critical buckling pressure, psi
- E = Modulus of tensile elasticity of the PVC material, psi
- I = Moment of inertia per unit length, $in^4/in = in^3$
- r = Mean radius of pipe, in.

With the Moment of Inertia (I) per unit length defined as $t^3/12$, Equation 18 can be rewritten:

EQUATION 19

$$P_{cr} = \frac{2E}{\left(\frac{OD - t}{t}\right)^3} = \frac{2E}{(DR - 1)^3}$$

Where:
- P_{cr} = Critical buckling pressure, psi
- E = Modulus of tensile elasticity of the PVC material, psi
- OD = Outside diameter, in.
- t = Wall thickness, in.
- DR = Dimension ratio, OD/t

For long tubes (pipelines) under stress, E must be replaced by $E/(1 - v^2)$ where v is the Poisson's Ratio ($v = 0.38$ for PVC pipe). Therefore, in PVC pipelines the critical wall buckling pressure can be properly calculated as follows:

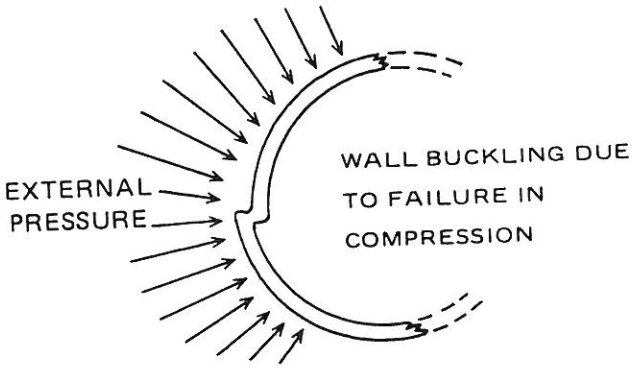
EQUATION 20

$$P_{cr} = \frac{2E}{(1 - v^2)(DR - 1)^3}$$

Note: This equation does not apply to profile wall pipes.

Where:
- P_{cr} = Critical buckling pressure, psi
- E = Modulus of tensile elasticity of the PVC material, psi
- DR = Dimension Ratio, OD/t
- v = Poisson's Ratio (0.38 for PVC pipe)

FIGURE 14
WALL BUCKLING



When pipes are buried or installed in such a manner that the soil or surrounding medium provides some resistance against buckling, the modified buckling pressure (P_b) in the soil has been found empirically to be:[3]

EQUATION 21

$$P_b = 1.15\sqrt{P_{cr}E'}$$

Where: P_b = Modified buckling pressure in a given soil, psi
P_{cr} = Critical buckling pressure, psi
E' = Modulus of soil reaction, psi

Analysis of PVC sewer pipe performance related to buckling pressure demonstrates that wall buckling of buried PVC sewer pipe cannot be considered a potential cause of line collapse in a typical sanitary sewer system:

> Example: If a DR 35 PVC sewer pipe with a 400,000 psi modulus of elasticity was confined in a saturated soil providing $E' = 200$ psi, what height (H) of the saturated soil which weighs 120 lbs/ft^3 (w) would cause buckling?

$$P_{cr} = \frac{2(400{,}000)}{[1 - (0.38)^2](35 - 1)^3} = 23.8 \text{ psi}$$

$$P_b = 1.15\sqrt{23.8(200)} = 79.34 \text{ psi} = 11{,}425 \text{ psf}$$

$$H = P/w = 11{,}425/120 = 95.2 \text{ feet}$$

Although it is improbable that the combined strength of a pipe/soil system can be exceeded when PVC sewer pipe is installed properly, excessive deflection is possible in extreme situations where major deficiencies are permitted in bedding and haunching of the buried pipe.

In conclusion, having analyzed and evaluated the potential and remotely possible modes of failure for buried PVC sewer pipe, it becomes obvious that for this flexible pipe product, inverse curvature or "ring buckling" (as opposed to wall cross-section compression buckling -- see Figure 14) is the critical failure mode.

In the development of a recommended design deflection limit, a *4:1* safety factor can be applied to the 30 percent deflection limit at which inverse curvature will be incipient for PVC sewer pipe. Therefore, the recommended design deflection limit for PVC sewer pipe, with a minimum pipe stiffness of 46 psi, is 7.5 percent.[3]

It must again be emphasized that design recommendations for each flexible pipe product must be based on the specific properties of that product.

Although inverse curvature of buried PVC sewer pipe will not occur normally at deflections under 30 percent, this may not be the case for other types of flexible pipe, which in most instances respond to critical modes of failure at deflections lower than those acceptable for PVC sewer pipe.

It should be noted that great attention was given to investigation of deflection performance limits for flexible pipes immediately following the publication of the Iowa Formula by Dr. Spangler. At that time, the most commonly accepted flexible pipe was corrugated steel culvert. Through research and field investigation, it was determined that corrugated steel pipe would begin to reverse curvature at a deflection of about 20 percent. It was substantiated through testing and evaluation that inverse curvature could be considered the critical failure mode in deflection for that product. Manufacturers and engineers, at that time, selected a *4:1* safety factor and developed the recommended design deflection limit of 5 percent for that product. Today, this recommendation is readily accepted by most designers of flexible steel pipe systems. Some engineers have not been properly informed regarding the derivation of the 5 percent deflection limit and thus continue to apply that limit to all flexible pipe products. However, with increased knowledge of each flexible pipe material's critical failure mode, this misunderstanding is becoming less common.

When comparing one flexible pipe product with another, it is important to compare first the critical failure modes related to deflection. Various modes of failure in deflection that should be considered for various other pipe products in addition to inverse curvature collapse and compression wall buckling may include:

- tensile rupture of structural members or fibers
- compression buckling of structural webs
- interlaminar separation in pipe wall

Having then compared maximum deflection limits at which failure can be anticipated, comparison of the selected factors of safety used to develop a recommended design deflection limit should be made. Safety factors selected to insure the structural integrity of any buried pipe system -- flexible or rigid -- are important. Although PVC sewer pipe is offered with a recommended design deflection limit of 7.5 percent providing a *4:1* factor of safety, flexible sewer pipe produced from other materials may be offered with a recommended design deflection limit of 5 percent providing factors of safety as low as *1.5:1*. As with rigid pipe products, it remains important that the engineer, installer, operator or owner knows his flexible pipe product -- its advantages and limitations.

Having evaluated PVC sewer pipe, the theory behind the product's strength in deflection, the laboratory research and field investigation which supports that theory and the performance limits which must be considered in selecting deflection limits and design recommendations, the need for deflection testing should be considered.

DEFLECTION TESTING

PVC sewer pipe when installed in accordance with ASTM D2321, "Standard Practice for Underground Installation of Thermoplastic Pipe for Sewers and Other Gravity-Flow Applications," will provide long-term performance with ring deflection less than the recommended limit of 7.5 percent. Deflection testing of properly installed PVC sewer pipe is unnecessary.

Deflection of buried PVC sewer pipe is essential to the proper performance of the product. Deflection is necessary to transfer the overburden load to the side fill for support. Deflection testing of buried PVC sewer pipe does not measure product quality. It is one of several methods that can be used to verify proper installation practices.[3] When proper installation practices are assured by construction inspection, soils testing, photography or television inspection, deflection testing is redundant.

With ring deflection of buried PVC sewer pipe maintained at or below the recommended 7.5 percent maximum limit, the design factor of safety provided to prevent structural failure of the

buried pipe will exceed *4:1*. With this large margin of safety, deflection testing of PVC sewer pipe is generally considered unessential to assure proper installation procedures.

Deflection testing will not be necessary unless in isolated sections of a sewer line one or more of the following conditions are known to exist:

- Improper construction practices are evident
- Questionable embedment materials have been used
- Severe trench construction conditions were encountered
- Other inspection or testing methods have indicated unacceptable installation conditions

When measuring the deflection of buried PVC sewer pipe it is important to recognize that accepted test procedures measure the deflected vertical inside diameter of the pipe.

Obviously, the selection of a proper base inside diameter for measurement of PVC sewer pipe deflection cannot be accomplished simply by subtracting two *minimum* wall thicknesses from the average outside diameter. In selection of a base inside diameter for deflection measurement, it is important to include reasonable manufacturing tolerances, since many PVC sewer pipe standards do not specify a minimum inside diameter and out-of-roundness tolerances, which take into account minor deformations which may occur as a result of shipping and handling prior to installation.

Many PVC pipe standards contain base I.D. values. The base I.D. is a pipe I.D. derived by subtracting a statistical tolerance package from the pipe's average I.D. The tolerance package is defined as the square root of the sum of squared standard manufacturing tolerances, as given below:

$$\text{Avg ID} = \text{Avg OD} - 2(1.06)t$$

$$\text{Tolerance Package} = \sqrt{A^2 + B^2 + B^2 + C^2}$$

Where:
- **A** = OD tolerance
- **B** = Excess wall thickness tolerance = 0.06t
- **C** = Out-of-Roundness tolerance
- **t** = Minimum wall thickness

When establishing the desired dimension for Go/No-Go mandrels used to test installed PVC sewer lines, the desired deflection limit is simply subtracted from the base inside diameter to establish the maximum outside diameter of the test mandrel.

Example: Calculate the maximum diameter for a Go/No-Go test mandrel to be used in the deflection testing of 8" PVC sewer pipe (ASTM D 3034 DR 35) with the design deflection limit selected as 7.5 percent. The Base I.D. of 8" DR 35, as listed in ASTM D 3034, is 7.665 inches.

$$\text{Mandrel OD} = \left[\frac{100 - \Delta Y}{100}\right] \text{x Base ID}$$

Where: ΔY = Deflection Limit, %

$$\text{Mandrel OD} = \left[\frac{100 - 7.5}{100}\right] \text{x } 7.665$$

Mandrel OD = 7.090 or *7.09 inches*

MANDREL DIMENSIONS

The outside diameter for a mandrel is calculated using a pipe's base inside diameter. The base inside diameters shown in Table 10 were calculated using the formulas shown on page 40 of this report or in Appendix X1 of ASTM D 3034-94. The outside diameter tolerance (A) was taken from Table 1 in ASTM D 3034. The wall thickness tolerance (B) is the customary 12 percent (6 percent for two walls) of minimum wall or 0.020 inch, whichever is greater (as done in other ASTM plastic pipe standards). The out-of-roundness tolerance (C) was derived statistically from field measurement data collected by ASTM members and appears in tabular form in Appendix X1 of ASTM D 3034-94. The base inside diameter listed is calculated by subtracting the statistical package from the pipe's average inside diameter. Some other mandrel dimensions, called out in the shop drawing in Figure 15, are specified in Table 10.

TABLE 10

BASE INSIDE DIAMETERS
7.5% DEFLECTION MANDREL DIMENSIONS
(FROM ASTM D 3034)

Nominal Pipe Size (In.)	Base Inside Diameter (In.)	O.D. of 7.5 % Deflection Mandrel (In.)	C* for 7.5% Deflection Mandrel (In.)	Max. L Req'd* for 7.5% Mandrel (In.)
6	5.742	5.31	4.31	6
8	7.665	7.09	6.09	8
10	9.563	8.84	7.84	10
12	11.361	10.51	9.51	12
15	13.898	12.86	11.86	15

*See Figure 15.

Using the same methodology, base inside diameters have been developed for pipe manufactured in accordance with ASTM F 679. Appendix X2 of ASTM F 679-89 lists the pipe's base inside diameters, the outside diameter for the deflection mandrel, and the out-of-roundness values. The first three columns of Table 11 come from Table X2.1 of ASTM F 679-89; the last two columns of the table list other pertinent mandrel dimensions. ASTM F 679 lists dimensions for both wall types: T-1 and T-2. Table 11, below, reproduces the dimensions for the type T-1 wall.

TABLE 11

BASE INSIDE DIAMETERS
7.5% DEFLECTION MANDREL DIMENSIONS
(FROM ASTM F 679)

Nominal Pipe Size (In.)	Base Inside Diameter (In.)	O.D. of 7.5 % Deflection Mandrel (In.)	C* for 7.5% Deflection Mandrel (In.)	Max. L Req'd* for 7.5% Mandrel (In.)
18	16.976	15.70	14.70	18
21	20.004	18.50	17.50	21
24	22.480	20.80	19.80	24
27	25.327	23.44	22.44	27

*See Figure 15.

Using the methodology detailed in the appendices of ASTM D 3034 and F 679 and on page 40 of this report, base inside diameters have been calculated for PVC pipe manufactured in accordance with ASTM F 789. The base inside diameters were calculated using the out-of-roundness tolerances for similar sized pipe from specifications D 3034 and F 679. The dimensions for the base inside diameter and 7.5% mandrel listed in Table 12 are those for the type T-1 product. The last two columns of Table 12 list other mandrel dimensions called out in the shop drawing in Figure 15. Dimensions for the type T-2 and T-3 product may be calculated in the same manner.

TABLE 12

BASE INSIDE DIAMETERS
7.5% DEFLECTION MANDREL DIMENSIONS
FOR ASTM F 789

Nominal Pipe Size (In.)	Base Inside Diameter (In.)	O.D. of 7.5 % Deflection Mandrel (In.)	C* for 7.5% Deflection Mandrel (In.)	Max. L Req'd* for 7.5% Mandrel (In.)
6	5.786	5.35	4.35	6
8	7.723	7.14	6.14	8
10	9.634	8.91	7.91	10
12	11.451	10.59	9.59	12
15	14.000	12.95	11.95	15
18	17.102	15.82	14.82	18

*See Figure 15.

Similarly, base inside diameters have been calculated for profile-wall pipe manufactured in accordance with UNI-B-9, "Recommended Performance Specification for Polyvinyl Chloride (PVC) Profile Wall Gravity Sewer Pipe and Fittings Based on Controlled Inside Diameter (Nominal Pipe Sizes 4 - 48 Inch)". (Refer to Table 13.) Open Profile, Closed Profile and Dual-Wall Corrugated Profile are types of profiles specified in the UNI-B-9 standard. The base inside diameters were calculated using the out-of-roundness tolerances for similar sized pipe from ASTM specifications D 3034 and F 679. Where no similar sizes existed, tolerances were extrapolated to the size.

TABLE 13

BASE INSIDE DIAMETERS
7.5% DEFLECTION MANDREL DIMENSIONS
FOR UNI-B-9 PIPE*

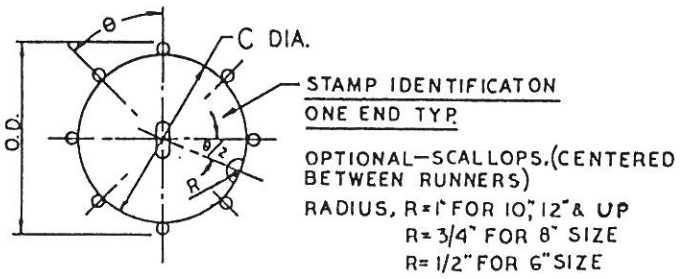
Nominal Pipe Size (In.)	Base Inside Diameter (In.)	O.D. of 7.5 % Deflection Mandrel (In.)	C** for 7.5% Deflection Mandrel (In.)	Max. L Req'd** for 7.5% Mandrel (In.)
4	3.864	3.57	2.57	4
6	5.725	5.29	4.29	6
8	7.637	7.06	6.06	8
10	9.525	8.81	7.81	10
12	11.312	10.46	9.46	12
15	13.828	12.79	11.79	15
18	16.923	15.65	14.65	18
21	19.956	18.46	17.46	21
24	22.600	20.90	19.90	24
27	25.446	23.54	22.54	27
30	28.350	26.22	25.22	30
33	31.249	28.91	27.91	33
36	34.106	31.55	30.55	36
39	37.003	34.23	33.23	39
42	39.880	36.89	35.89	42
45	42.762	39.56	38.56	45
48	45.639	42.22	41.22	48

* Due to the similarities of the UNI-B-9 product and the ASTM F 794 and F 949 products, the mandrel dimensions listed can be considered appropriate for use with these standards.

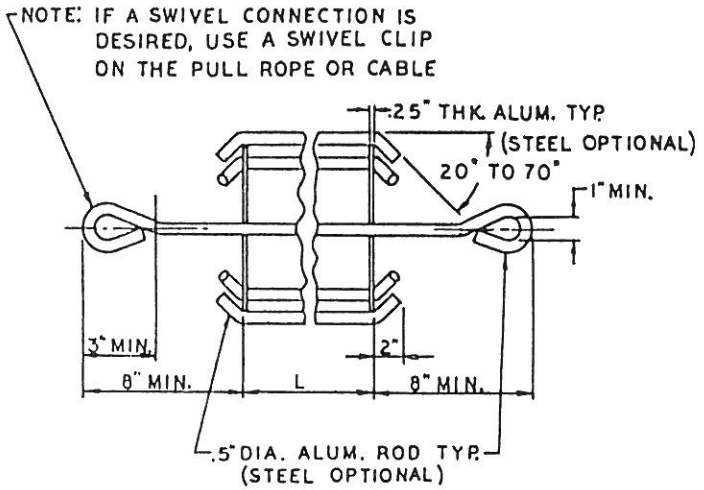
**See Figure 15.

FIGURE 15

SHOP DRAWING FOR DEFLECTION MANDREL



NUMBER OF RUNNERS	7	8	9	10	11	12
ANGLE θ	51.4°	45°	40°	36°	32.7°	30°



NOTES:
* ALL DIMENSIONS IN INCHES.
* STAMPED IDENTIFICATION SHALL INDICATE PRODUCT STANDARD, DIMENSION RATIO, AND PIPE DIAMETER.
* O.D., C, AND L FOUND ON TABLES 10, 11, 12 & 13.
* TOLERANCE + 0.000" - 0.040" FOR O.D & C.
* TOLERANCE +/- 1/16" FOR L.
* OVERALL LENGTH OF RUNNER MAT'L REQ'D = L + 4".
* OVERALL LENGTH OF CENTER ROD MATERIAL REQ'D = L + 26".
* MANDREL SHALL BE SIZED FOR 7 1/2 % DEFLECTION LIMIT.

UNI-BELL PVC PIPE ASSOC.
2655 VILLA CREEK DR., SUITE 155, DALLAS, TX., 75234 (972/243-3902)

NO.	REV.
2	REDRAWN 3-25-97
1	REDRAWN 10-21-94

DETAIL -- FAB & ASSY
GO / NO - GO MANDREL
FOR DEFLECTION
TESTING OF INSTALLED
GRAVITY SEWER PIPE

DATE: 3-25-97 C.F.
DWN: C.F. NO SCALE
UNI-TR-1-97

SUMMARY

The vast array of data from laboratories and field installations throughout the world clearly substantiates that PVC sewer pipe must deflect within certain tolerable limits in order to perform properly as part of a buried flexible conduit system. Engineers and contractors in general have come to realize that deflection in the product is not a source of fear, but, rather, a source of significant benefit.

With a proper understanding of deflection in PVC sewer pipe, the engineer, installer, operator or owner can evaluate properly the significant benefits provided by deflection in PVC sewer pipe. He can also analyze the potential problems which he can anticipate if clearly "excessive" deflections have been realized in his PVC sewer system. With a clear understanding of the deflection failure limits for the product, he may choose to classify a short section of substantially deflected PVC sewer pipe caused by heaving soils, shifting manholes, unstable trench foundation or point-loading from rocks and debris as a good example of the deflection mechanism working to his benefit. The pipe deflection can prevent the shear break, beam break, joint break or crack which could have been anticipated under those circumstances when using some rigid or less flexible pipe products. Deflection capability in a buried sanitary sewer pipe is a performance benefit.

BIBLIOGRAPHY

1. *Webster's New World Dictionary of the American Language*, The World Publishing Company, Cleveland and New York (1957).

2. Spangler, M. G. and R. L. Handy, *Soil Engineering*, Intext Educational Publishers, New York, NY (1973).

3. *Handbook of PVC Pipe: Design and Construction*, Uni-Bell PVC Pipe Association, Dallas, TX (1993).

4. "Standard Test Method for Determination of External Loading Characteristics of Plastic Pipe by Parallel-Plate Loading - ASTM D 2412," American Society for Testing and Materials, West Conshohocken, PA (1993).

5. *Design and Construction of Sanitary and Storm Sewers*. ASCE Manual and Report on Engineering Practice No. 37. (WPCF Manual of Practice No. 9) American Society of Civil Engineers and the Water Pollution Control Federation, New York, NY (1974).

6. Moser, A. P., R. K. Watkins and O. K. Shupe, "Design and Performance of PVC Pipes Subjected to External Soil Pressure," Buried Structures Laboratory, Utah State University, Logan, UT (June 1976).

7. Moser, A. P., "Can Plastic Sewer Pipe Be Installed With 100% Confidence?" Presentation at the 68th Annual Meeting of the ASSE, New Orleans, LA (Oct. 1974).

8. Watkins, R. K., A. P. Moser and R. R. Bishop, "The Structural Performance of Polyvinyl Chloride Pipe Subject to External Soil Pressure," Engineering Experimental Station, Utah State University, Logan, UT (June 1973).

9. "PVC Pipe - Technology Serving the Sewer Industry," Uni-Bell PVC Pipe Association, Dallas, TX (1977).

10. "Standard Specification for Type PSM Poly(Vinyl Chloride) (PVC) Sewer Pipe and Fittings - ASTM D 3034," American Society for Testing and Materials, West Conshohocken, PA (1994).

11. Howard, Amster K., "Modulus of Soil Reaction (E') Values for Buried Flexible Pipe," *Journal of the Geotechnical Engineering Division*, ASCE, Vol. 103, No. GT, Proceedings Paper 12700 (Jan. 1977).

12. Marston, Anson and A. O. Anderson, "The Theory of Loads on Pipes in Ditches and Tests of Cement and Clay Drain Tile and Sewer Pipe," Bul. 31, Iowa Engineering Experiment Station, Ames, IA (1913).

13. Timoshenko, S. P., *Strength of Materials, Part II - Advanced Theory and Problems*, Van Nostrant Company, Princeton, NJ (1968).

14. "Standard Practice for Underground Installation of Thermoplastic Pipe for Sewers and Other Gravity-Flow Applications - ASTM D2321", American Society for Testing and Materials, West Conshohocken, PA (1989).

15. Janson, Lars-Eric and Jan Molin, "Design and Installation of Underground Plastic Sewer Pipes," *Proceedings of the International Conference on Underground Plastic Pipe*, ASCE, New York, NY (1981) pp. 79-88.

16. Janson, Lars-Eric, "Plastic Gravity Sewer Pipes Subjected to Constant Strain by Deflection," *Proceedings of the International Conference on Underground Plastic Pipe*, ASCE, New York, NY (1981).

17. Jensen, Brent M., "Investigations of Strain Limits Proposed for Use in Designing PVC Pipe Subjected to External Soil Pressure," Master of Science Thesis, Utah State University, Logan, UT (1977).

18. Moser, A. P., "Strain as a Design Basis for PVC Pipe?" *Proceedings of the International Conference on Underground Plastic Pipe*, ASCE, New York, NY (1981) pp. 89-103.

19. Moser, A. P. and O. K. Shupe, "Inverse Curvature of PVC Pipe Subjected to Soil Loadings," Buried Structures Laboratory, Utah State University, Logan, UT.