NSF/RA-790036

PB 296180

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SUGGESTED EXPERIMENTS
ON STRAIGHT PIPES IN AIR AND IN SOIL

By

R.J. Kratky, I. Nelson, M.G. Salvadori and P. Weidlinger

Grant Report No. 9

Prepared for

National Science Foundation (ASRA Directorate)
1800 G Street
Washington, D.C. 20550

Grant No. PFR 78-15049

JANUARY 1979

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ABSTRACT

The report discusses a series of suggested static and dynamic tests on straight pipes in air and in soil, aimed at obtaining experimental values of the parameters appearing in the dynamic analysis, and in the Damage Matrices presented in Reports IR-3, 3a and 5.

The report contains a brief analytical study of the translational behavior of such pipes and a complete, organized bibliography on the tests performed to date on such and other pipelines in the U.S. and abroad.

Any opinions, findings, conclusions or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

1. Purpose and Scope of Report

An analytical investigation of the behavior of underground lifelines must of necessity rely on experimentally obtained data. The purpose of such experimental data is to:

a) verify the assumed ground motion input,

b) determine the ground motion characteristics, for various site conditions, relevant to lifeline design,

c) acquire the physical constants relevant to the static and dynamic behavior of lifelines,

d) verify analytical models,

e) verify the predictions of pipeline response behavior, and seismic design criteria.

At the present state of Weidlinger Associates' (WA) analytical research work, the need for experimental data for all the above purposes has become increasingly obvious, since the major objective of the research, namely that of the presentation of simplified design guidelines, will necessarily incorporate many empirical constants and semi-empirical procedures.

The purpose of this report is to provide a broad outline of a fairly complete experimental program together with a somewhat more detailed description of those phases of the program which are of immediate concern.

2. Experimental Categories

The experimental program may be separated into the following four categories:

a) Free Field Data Acquisition

The free field data should be obtained through the placement of arrays of strong motion accelerometers to measure the relative motion of adjacent points at or near the surface. These instruments should have a common time scale so that the arrival time at each instrument of various components of the seismic signals may be ascertained.

Such measurements provide the basic input for the seismic calculations by defining what has been termed the "non-coherent" component of the free field (Ref. 1). It will provide clarification and information on incoherent motion by:

i) determining phase delay interference effects;

ii) measuring phase velocity phenomena;

iii) clarifying the effect of inhomogeneities.

The preferred method to obtain such data is to monitor actual seismic events, but incoherent ground motions could also be monitored in large scale explosive field tests. However, since the character and frequency content of ground motions due to explosions differ in significant aspects from those due to natural events, the interpretation of data thus obtained may be difficult. Preliminary work will be required prior to initiation of such experimentation (Ref. 2).

b) Verification of Systems Behavior

The objective of these tests is the experimental verification of the suggested prediction methodology for the behavior of systems and components using both a deterministic and a probablistic approach.

This may require large scale explosive field tests, which, however, may present the difficulties mentioned in a) above. Reduced scale, and even some full scale experimentation in the laboratory,can be performed on shake tables (Ref. 3). WA's analytical work is not sufficiently advanced to warrant proof-testing at this time, but, upon completion of the current phase of research, such procedures will be proposed.

c) Damage Matrices Input

An important phase of the ongoing work is the development of Damage Matrices (Ref.4). These proposed matrices will define the failure and service limit criteria for various systems and components to be used in the design and evaluation of underground lifelines.

Some elements of these matrices are determined analytically at present, whenever the required physical constants of the material are available, as is the case for continuous steel pipelines and, to a limited extent, for jointed pipelines. In the latter case, because the properties of joint materials are not well defined and because some failure modes cannot be easily treated analytically, experimental verification and data acquisition are essential.

The corresponding tests need to be performed, under laboratory conditions if possible, on full scale specimens for a variety of static loadings and imposed deformation conditions.

Some of this information may be obtained from experimental programs on pipes under non-seismic operating conditions conducted in earlier investigations. To this purpose WA hopes to obtain the cooperation of industry and other interested user organizations so that some of their requirements may be included in their experimental programs.

d) Measurement of Dynamic Characteristics

The current trend of WA's analysis indicates that component and systems response to seismic excitation may be either essentially static or predominantly dynamic. This latter case is probably significant for large diameter jointed pipe systems in combination with terminal and nodal points. To deal with these dynamic phenomena, equivalent multi-degree of freedom system analytical models are being developed, and, for the previously mentioned reasons, the dynamic pipe parameters (stiffness and material damping) in various modes of free vibration (in air) required by the models must be measured experimentally.

e) Measurement of Interaction Parameters

i) In the cases where the anticipated interaction response are quasi-static, the interaction of the system with the soil medium is negligible, except for the case of the response to compressive strain. In this case, static buckling or other instabilities are likely to be strongly affected by the surrounding medium, and the determination of the relevant parameters must be obtained by measurements from static experiments on components submerged in the medium. Such experiments may be performed on either full or reduced scale specimens.

ii) In the case where the anticipated interaction responses have dynamic characteristics, the interaction frequencies and the radiation damping of the system are predictable by analytical methods, under certain simplified assumptions. It is essential that these predictions be validated by actual measurement.

The following detailed discussion of the experimental program is restricted to items c), d), and e) of the above outline, and addresses itself to experimental support requirements consistent with the progress of the ongoing research.

3. Discussion of the Experimental Program

a) Test classification categories and bibliography

Tests and reports, to provide comprehensive data for the establishment of Damage Matrices (for leakage and failure), the dynamic characteristics of the pipes and their joints, and the interaction parameters of the pipe-soil system may be obtained from two sources.

The first is to be found in available reports providing pertinent data. Appendix "A" (see pp. 33-63) provides a bibliography of references to such test reports, subdivided in 12 (somewhat arbitrary) groupings to facilitate summarizing the total spectrum of completed tests. Each grouping is classified by a heading and includes a general discussion of the test reports contained in that group. The group headings are:

i. Recent work by the Bureau of Reclamation

ii. Recent work done in Japan,

iii. Recent work on soil-interaction,

iv. Performance of rigid concrete pipes,

v. Performance of buried pipes and culverts,

vi. Recent hydrostatic and waterhammer tests,

vii. Gasketed bell-and-spigot joints,

viii. Buckling in soil media,

ix. Tube bending,

x. Forces on cylinders,

xi. Branched connection behavior,

xii. Behavior of buried pipes under horizontal and vibratory motions.

The second source of information will be found in the series of previously performed tests and new tests suggested below.

b) Available Static Tests

An outline of the general classifications of already available testing procedures is shown in Table I. It presents the kind of static testing that has been used for designing pipelines under normal loading conditions. These tests accomplish the following:

i. Three-Edge Bearing tests establish the ring crushing and cracking loads for a pipe segment continuously supported on two bearing edges at the bottom, and loaded at its crown by a continuous line load (see Fig. 1).

TABLE I

Available Static Tests

Type of Force or Deformation	Medium	
	In air	In the soil
Ring	1) Three-edge bearing 2) Hydrostatic	3) In trench 4) In embankment
Segment	5) Simple beam bending	
Joint	6) Shear	

TABLE II

Phase I-Tests for Extensional Static and Dynamic Behavior of Straight Pipes

Medium	In air		In the soil	
Loading / Pipe type	Static	Dynamic	Static	Dynamic
Jointed	(7)	(8)	(9)	(10)
Continuous	(11)	(12)	(13)	(14)

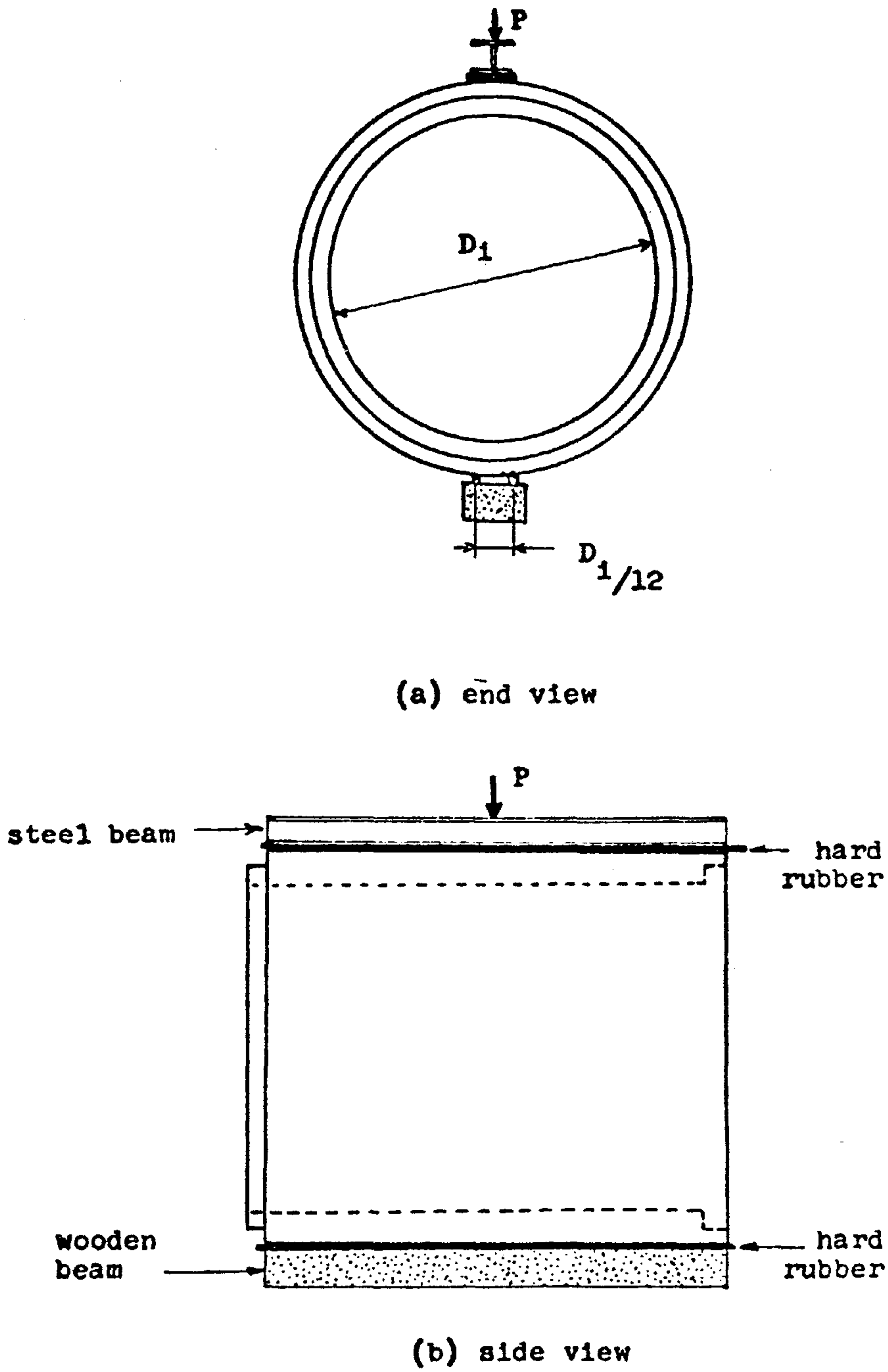


FIG. 1 Three-edge Bearing Test
ASTM C 497

ii. Hydrostatic tests proof-load pipe ring segments for leakage up to two or three times the normal working pressure.

iii&iv. Load-Deformation tests on in-situ pipe ring segments, in either trench (iii) or embankment (iv) conditions, establish the pipe-ring soil interaction behavior.

v. Simple-beam bending tests establish the ultimate bending moment of pipe segments.

vi. Joint shear-tests establish the ultimate shear capacity of the gasketed bell-and-spigot joint.

c) Suggested Tests of Immediate Interest

The suggested tests should be performed in order to support current and future research work by determining the damage matrix parameters and the relevant dynamic characteristics of pipes.

The first category of such tests, which are of immediate interest for the current research,constitutes Phase I of the test program and involves only extensional static and/or dynamic tests of continuous and jointed pipes in air and in the soil. These tests are listed in Table II.

Bent pipes, pipes with tee-joints, pipe anchorages and other pipe-network connections should be included in Phase II of the test program, and be performed immediately after the straight pipe behavior is determined.

The major input variables for such tests are:

i. the pipe material,

ii. the pipe construction type,

iii. the pipe diameter,

iv. the level of hydrostatic pressure for normal and surge conditions,

v. the type of joint.

vi. the type of grout and/or gasket,

vii. the depth of burial,

viii. the type of trench or embankment

ix. the type of bedding, and

x. the type of soil and its compaction.

The major output variables to be obtained from these tests are:

xi. the static and dynamic serviceability limits,

xii. the static and dynamic material failure limits,

xiii. the peak amplitude response to the dynamic excitation, and

xiv. the coefficient of critical damping.

d) Additional Suggested Tests of Future Interest

These involve static and dynamic tests of pipe segments and joints in air and in the soil, with the same input and output variables (whenever pertinent) as those under c) to assess their:

i. buckling loads,

ii. bending strength,

iii. shear strength,

iv. torsional strength.

e) Damage Matrices and Test Schemes

Tables III and IV are examples of portions of the Damage Matrices for an 18" diameter cast iron pipe, and a 30" diameter prestressed concrete cylinder (PCC) pipe, showing only the relevant <u>extensional</u> characteristics, which have been obtained through analytical methods. Complete Damage Matrices encompass a much broader range of types of stresses and deformations,

TABLE III — DAMAGE MATRIX

18" DIAMETER - 18/40 CAST IRON PIPE
CONNECTED WITH A RUBBER GASKETED MECHANICAL JOINT
WITH 12 - 3/4" φ BOLTS

PIPE CHARACTERISTICS

TYPE OF PIPE STRESS	TYPE OF FAILURE FORCE OR ELONGATION	ULTIMATE FORCE / DISPL.	UNITS
EXTENSIONAL	AXIAL TENSION	672,256	lbs.
	AXIAL COMPRESSION	3,361,300	lbs.

JOINT CHARACTERISTICS

TYPE OF DEFORMATION	TYPE OF FAILURE OR LEAKAGE FORCE OR DISPLACEMENT	ULTIMATE FORCE / DISPL.	UNITS
EXTENSIONAL	BOLT FAILURE IN TENSION	180,630	lbs.
	BOLT FAILURE IN BENDING	6,834,000	in-lbs.
	GASKET SLIPPAGE FAILURE	148,872	lbs.
	GASKET LEAKAGE	8,839	lbs.
	MAX ELONGATION	0.5	in.

TABLE IV - DAMAGE MATRIX

PCC PIPE - 30" DIAM. x $1\frac{7}{8}$" CORE

PIPE CHARACTERISTICS

TYPE OF PIPE STRESS	TYPE OF ULTIMATE FORCE	ULTIMATE FORCE	UNITS
EXTENSIONAL	LONGITUDINAL COMPRESSION	1,762,100	lbs.
	LONGITUDINAL TENSION	469,800	lbs.

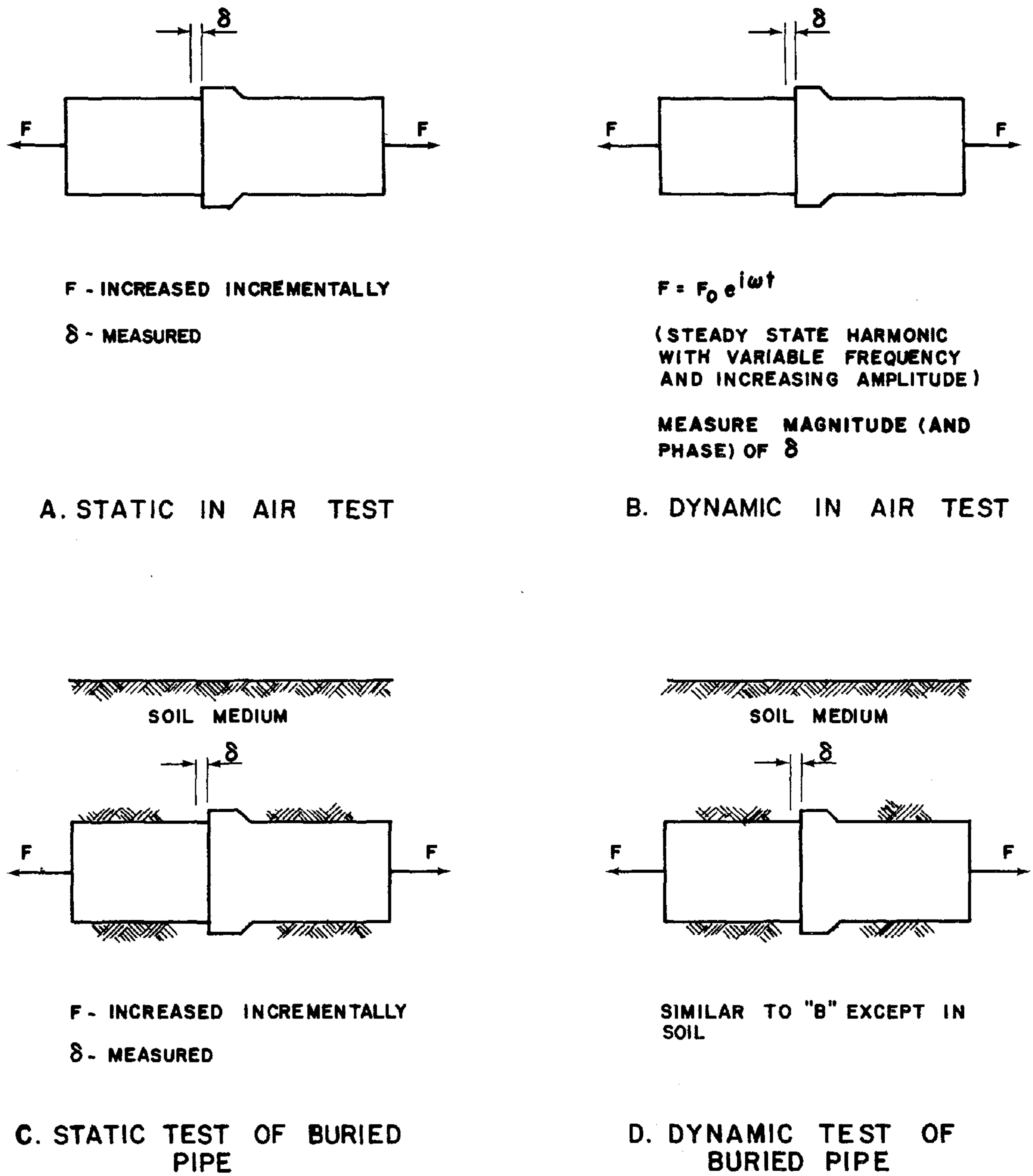
JOINT CHARACTERISTICS

$21/32$" φ RUBBER GASKET, P_W = 150 psi, 20' SEGMENT

TYPE OF DEFORMATION	TYPE OF LEAKAGE FORCE OR DISPLACEMENT	LEAKAGE FORCE	UNITS
EXTENSIONAL	LONGITUDINAL TENSION	12,235	lbs.
	LONGITUDINAL COMPRESSION	1,281,500	lbs.
	MAX. LONGITUDINAL EXTENSION	0.375	in.

including circumferential, translational, rotational and torsional stresses and deformation. For continuous or unjointed pipes, only the pipe characteristics in Tables III and IV are required to establish the limits of extensional failure of the pipe. For jointed pipelines, only the joint characteristics in Tables III and IV are required to determine the serviceability limits for leakage. The leakage limits for extension shown in Tables III and IV are those established by the industry for normal service conditions. These leakage limits and the analytically determined pipe and joint characteristics will be verified by the static and dynamic tests 7 and 8 in Table II. These tests will, at the same time, define the pipe joint stiffness characteristics (in air) and establish their non-linear behavior.

A schematic representation of the tests to be performed on a given pipe is shown in Fig. 2. In each sequence of testing a specific pipe model would be tested in air and under a given hydrostatic head of water and load tested to failure by incremental static loads. The tests would establish the pipe and joint characteristics described in 2c) above, and also serve to calibrate the instrumentation for future dynamic tests. The test set-up would then be altered to subject the identical models to steady state harmonic loadings under pressurization from air and water. The purpose of testing the dynamic models with air pressurization is to define the character and peaks of the frequency response curves in air and the associated percentages of critical material damping. The tests under hydrostatic pressure are to ascertain the effect of the water on the apparent mass and damping characteristics of the pipe-water system.



NOTE: IN ALL TESTS THE PIPES ARE INTERNALLY PRESSURIZED WITH AIR OR WATER

FIG. 2 STATIC AND DYNAMIC TESTS FOR JOINT EXTENSION

The purpose of the dynamic tests in the soil is to establish the combined effect of material and radiation damping for the pipe-soil system and to define the peak and character of the frequency response curve for the pipe in the soil.

4. Mathematical Analysis and Tests of the Extensional Behavior of Jointed and Continuous Pipes

a) Pipe Equations

The dynamic analysis of the axial motion of a long, segmented buried pipe was considered in Refs (5) and (6). The pipe was modeled as a series of rigid links connected by springs and dashpots, and attached to the ground via an axial Winkler type foundation, Fig. 3 . The equation of motion of the typical i^{th} link is given in Refs (5) and (6) as:

$$\begin{aligned} m\ddot{x}_i + c_g\dot{x}_i - c_p(\dot{x}_{i-1} - 2\dot{x}_i + \dot{x}_{i+1}) + k_g x_i \\ - k_p(x_{i-1} - 2x_i + x_{i+1}) = c_g\dot{z}_i + k_g z_i \end{aligned} \tag{1}$$

where the various quantities are defined in Fig.4. In addition to the segment length ℓ, there are five parameters which describe the system. The mass m includes the mass of the pipe segment plus possible contributions from the enclosed water and the surrounding soil. These latter two are most likely frequency dependent. The quantity k_p is the axial

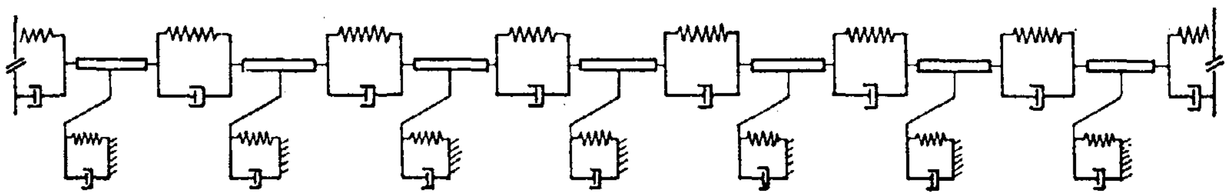


FIG. 3 LONG JOINTED PIPE SUPPORTED BY SPRINGS AND DASHPOTS (AXIAL MOTION ONLY CONSIDERED)

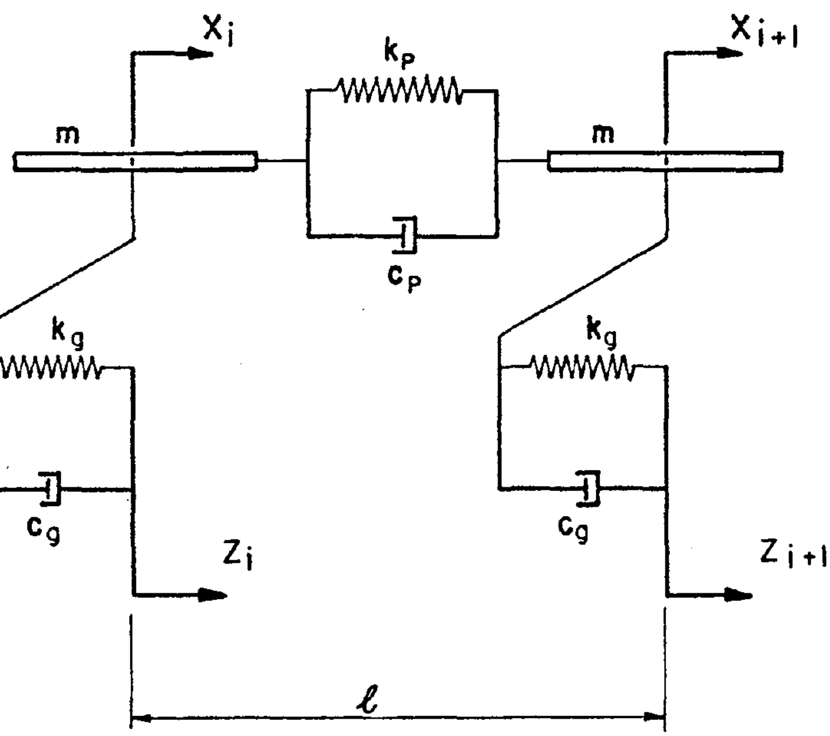


FIG. 4 TWO UNDERGROUND PIPE SEGMENTS CONNECTED BY JOINT

stiffness of the joint. Presumably, as the grout begins to crack under increasing load, the tangent stiffness will decrease. Moreover, if the joint material is viscoelastic, k_p will vary with frequency as well. The damping coefficient c_p may be determined from the hysteresis found in a joint load-unload cycle. Usually the damping ratio ξ_p rather than c_p is of interest, where the fraction of critical damping is:

$$\xi_p = \frac{c_p}{2\sqrt{m_p k_p}} \qquad (2)$$

It should be noted that if the actual energy loss per cycle is independent of frequency, then ξ_p must vary with frequency. Moreover, when the pipe is filled with water, the viscosity of the water will lead to additional damping, particularly at high frequencies. Preliminary analysis of the interaction of water in a long longitudinally oscillating pipe suggests that both the added mass and damping terms are small for the practical range of frequencies, Ref. (7).

When the pipe is placed in the soil, the situation becomes more complicated. In addition to a possible added mass of soil, the parameters k_g and c_g represent the overall effect of the soil on the stiffness and damping of the system. The damping includes both radiation and material damping. Wright and Takado [Ref. (8)] indicate that,both for a continuous pipe and a segmented pipe buried in an elastic medium, the added mass may be neglected, and that k_g and c_g vary slowly with frequency.

b) In Air Static Tests of Jointed Pipes - Extensional Deformation, Test (7). These static tests in air can be used to determine the extensional stiffness properties and non-linearities of the jointed pressurized pipeline (both grouted and ungrouted). The main objective of the tests would be to measure the joint extension as a function of applied load and level of hydrostatic pressure for specific kinds and sizes of pipes. These tests will record the limiting load for joint leakage and the extension at which this occurs. These may then be compared to the analytically derived values found in the Damage Matrices. For example, the joint characteristics of the Damage Matrices for an 18" diameter Cast Iron pipe and a 30" diameter Prestressed Concrete Cylinder (PCC) pipe are given in Tables III and IV. These give a limit load for gasket leakage of 8,839 lbs for the 18" cast cast iron pipe, and 12,235 lbs for the 30" PCC pipe. The maximum extensions at leakage given in these tables are 0.5 in for the 18" cast iron pipe and 0.375 in for the 30" PCC pipe. These tests should be carried through to ultimate failure load of the joint and again this limit may be correlated with failure data for the joint characteristics in the Damage Matrices. For the 18" cast iron pipe shown in Table III, the gasket slippage failure load is 148,872 lbs and the bolt failure load for extensional tension is 180,630 lbs. These static tests may also serve to calibrate the instrumentation for subsequent dynamic and buried pipe tests. The results of the tests will help to verify and check the assumption made in analytically determining the linearized mean stiffness properties of the jointed pipe. A typical example of these linearized joint stiffness properties for extension that have been determined analytically for two rubber gasketed concrete pipes is shown in Table V. The extent of the non-linear behavior and appropriate quasi-static stiffness in various regimes will be determined by these tests.

c) In Air Dynamic Test of a Jointed Pipe - Extensional Motion, Test (8). Dynamic tests would be run on a similar pipe/joint system as that used in the static test described under b). An example of a simple test configuration is shown in Fig. 5. A single pipe segment, so supported as to avoid development of horizontal friction, is attached by typical joints to (partial) pipe segments on either side which are held firmly in place. (In Fig. 5 the absence of friction is symbolized by "roller supports.") The two far ends are capped with flexible membranes to withstand the hydrostatic internal pressure. The middle segment is subjected to a harmonic force $F_o e^{i\omega t}$, and the resulting displacement $x(t)$ is measured.

At first the test is run with air pressurization at a pressure typical of those in piping systems. The choice of the initial magnitude of F_o will be based on the results of the static test. Once a steady state is reached, the displacement is:

$$x(t) = x_o e^{i(\omega t-\delta)} \tag{3}$$

One measure of the response is the variation of x_o/F_o with frequency, Fig. 6a. By comparing the maximum observed x_o/F_o and the frequency at which it occurs, ω_m, with the response of a single degree of freedom

TABLE V

RUBBER GASKETED JOINTED CONCRETE PIPES

TYPE OF PIPE	WORKING PRESSURE	EXTENSIONAL MODE		
		STIFFNESS	PERIODS—FULL & EMPTY	
		K_x (#/")	$T_{x,f}$ (sec.)	$T_{x,e}$ (sec.)
PCC 30" DIAM 20' LGTH	150 PSI	27.660×10^3	0.216	0.155
PCEC 60" DIAM 20' LGTH	150 PSI	25.835×10^3	0.440	0.311

1. ABOVE VALUES BASED ON 20°F AMBIENT PIPE TEMPERATURE.
2. GASKET DEFLECTION DUE TO INSTALLATION ASSUMED TO EQUAL 35%; GASKETS TO UNDERGO A 20% STRESS RELAXATION AFTER 20 YEARS.
3. A NO INTERFERENCE CONDITION IS ASSUMED AT THE JOINT (NO STEEL TO STEEL BINDING).

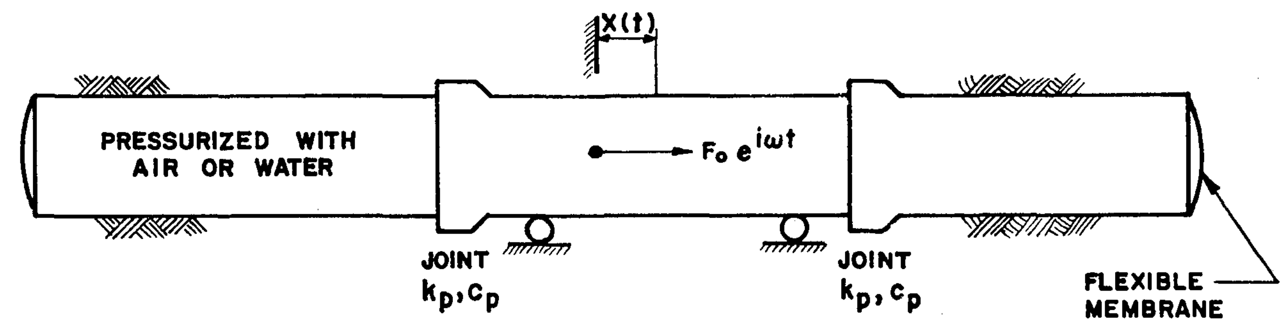
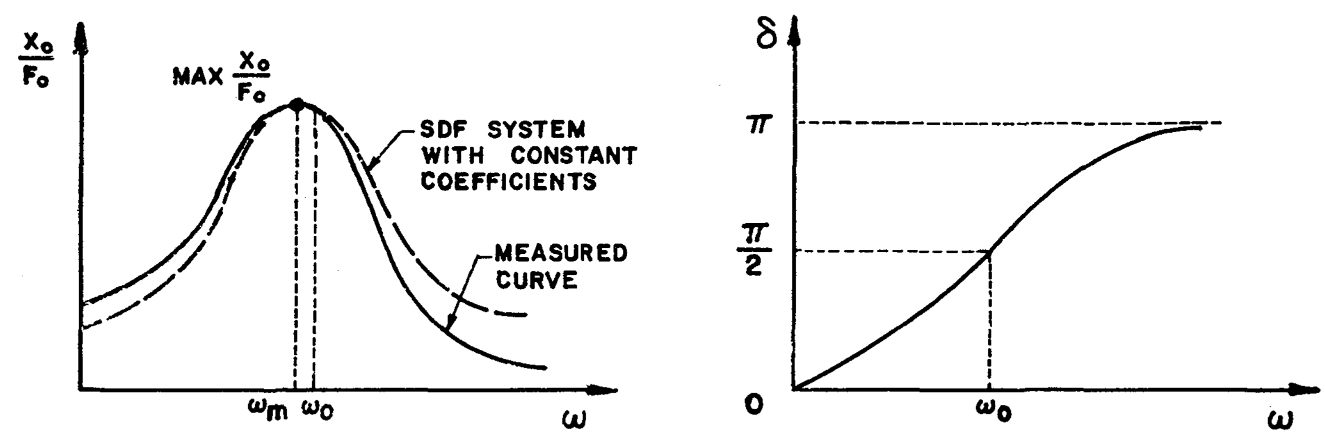


FIG. 5 IN AIR DYNAMIC TEST OF A JOINTED PIPE



a) AMPLIFICATION X_o/F_o

b) PHASE ANGLE δ

FIG. 6 RESPONSE MEASUREMENTS IN A DYNAMIC TEST

oscillator with constant coefficients, one may determine both $k_p(\omega_m)$ and $c_p(\omega_m)$. However, at frequencies away from resonance, the two curves will differ (see Fig. 6a). If at every frequency the phase angle δ is measured as well (Fig. 6b), the variation of $k_p(\omega)$ and $c_p(\omega)$ may be determined. In particular, at the frequency ω_o at which the phase angle δ crosses $\pi/2$:

$$2k_p(\omega_o) = m\omega_o^2 \tag{4}$$

and:

$$\omega_o 2c_p(\omega_o) = 1/[x_o/F_o(\omega_o)] \tag{5}$$

(where the two's appear because of the two joints).

After the test has been completed at a particular loading level F_o with air in the pipe, it should be repeated with the pipe filled with water. The "flexible" end caps prevent the fluid end conditions from affecting the response in the test section. An alternate procedure would be to replace the end caps with large reservoirs.

Finally, the entire test sequence (in the complete frequency range with, first, internal air and, then, water present) is repeated using a larger loading intensity F_o. In this way the nonlinear behavior can be determined.

d) Static Test of Buried Jointed Pipe - Extensional Motion, Test (9).
The configuration shown in Fig. 5 is next buried in a soil bin. Hence, the "frictionless rollers" under the test section are now replaced by soil. Care should be taken that i) the soil bin be large enough

(several pipe diameters) so that the in situ condition is approximated, and ii) the laying condition and backfill follow typical field practice. The pipe is then pressurized and loaded statically and the resulting load deformation curve is plotted, Fig. 7a. By subtracting the tensile and compressive pipe/joint forces at the corresponding deformation (obtained from test 7), Fig. 7b, from the applied load, the static ground force/deformation relation is obtained, Fig. 7c.

The static test affords one the opportunity to check out the apparatus and debug the system before commencing dynamic testing.

e) Dynamic Test of Buried Jointed Pipe - Extensional Motion, Test (10).

Dynamic tests would be performed on a buried pipe model identical to that used in dynamic test 8 under c). The purpose of these tests would be to establish the extensional response curve, x_o/F_o (Fig. 6a) and, if possible, the phase angle δ (Fig. 6b) as a function of frequency for each level of loading. In addition, the tests could be used to determine the initiation of slippage and the parameters influencing it.

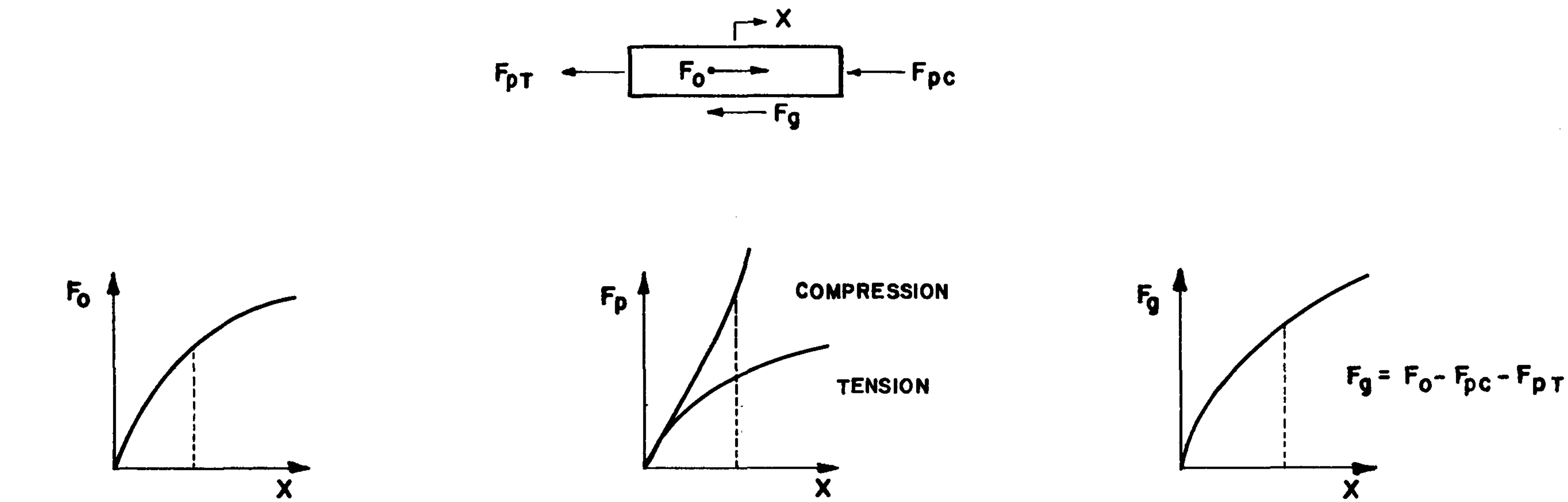
For the configuration considered, the equation of motion in terms of the parameters in Eq. (1) is:

$$m\ddot{x} + (c_g + 2c_p)\,\dot{x} + (k_g + 2k_p)x = F_o e^{i\omega t} \qquad (6)$$

The natural frequency of the undamped system is:

$$\omega_o^{\,2} = \frac{k_g(\omega_o) + 2k_p(\omega_o)}{m(\omega_o)} \qquad (7)$$

and will occur when the phase angle δ crosses $\pi/2$. In particular, if in the vicinity of resonance any added mass may be neglected, the



a) MEASURED STATIC RESPONSE

b) STATIC PIPE RESPONSE FROM TEST 7

c) STATIC GROUND RESPONSE

FIG. 7 STATIC GROUND FORCE DEFORMATION RESPONSE

appropriate value of k_g to use for a multidegree of freedom system is:

$$k_g = m_p\omega_o^2 - 2k_p(\omega_o) \tag{8}$$

where everything on the right had side of Eq (8) has already been determined. Likewise,

$$c_g = \frac{1}{\omega_o}\left[[x_o/F_o(\omega_o)]^{-1} - 2c_p(\omega_o)\right] \tag{9}$$

The test is next repeated with a larger load F_o.

f) Static Test In Air of Continuous Pipe - Extensional Mode, Test (11). For pipe materials such as steel, whose stress-strain properties are well documented, the static air test is not necessary. However, for other newer materials such as reinforced plastics, it will be necessary to establish the axial force deformation characteristics of the pressurized pipe. This test will also serve to check out the apparatus for the dynamic test.

g) Dynamic Test In Air of Continuous Pipe - Extensional Motion, Test (12). Again, for pipe materials such as steel, where the stiffness is known to be independent of frequency, and where estimates of the structural damping are available, dynamic testing in air serves no useful purpose. (It is assumed that the question of the effect of the internal water was settled when jointed pipes, under section c), were considered.) However, for the newer plastic materials, which are most likely viscoelastic, the in air dynamic test would establish the pipe stiffness and damping as functions of frequency.

h) Static Test of Buried Continuous Pipe - Extensional Mode, Test (13). The configuration shown in Fig. 5, which was suggested for testing buried jointed pipes, is not appropriate for continuous pipes, since the movement of the end section will be of the same order as that of the mid-span section. The solution will then be sensitive to how well the ends are "fixed." An alternate configuration is suggested in Fig. 8a, where "stiff" end caps attached to the continuous buried pipe protrude through "frictionless" sleeves from the ends of the soil bin. The forces F_1 and F_2 are applied to the end caps of the pipe and the corresponding displacements u_1 and u_2 are measured.

A simplified model fo the test configuration is shown in Fig. 8b, where following Refs (7) and (8) it is assumed that any added mass of water or soil may be neglected in practical frequency ranges. The Young's modulus E, the cross-sectional area A and the density ρ all refer to the pipe, while k_s and c_s are distributed interaction spring and dashpot coefficients, respectively (k_s = force/unit displacement/unit length and c_s = force/unit velocity/unit length). Obviously, for similar pipe materials, diameters, soil/laying conditions and frequency, they are related to the discrete system parameters k_g and c_g via:

$$k_s = k_g/\ell \tag{10}$$

and:

$$c_s = c_g/\ell, \tag{11}$$

where ℓ is the segment length.

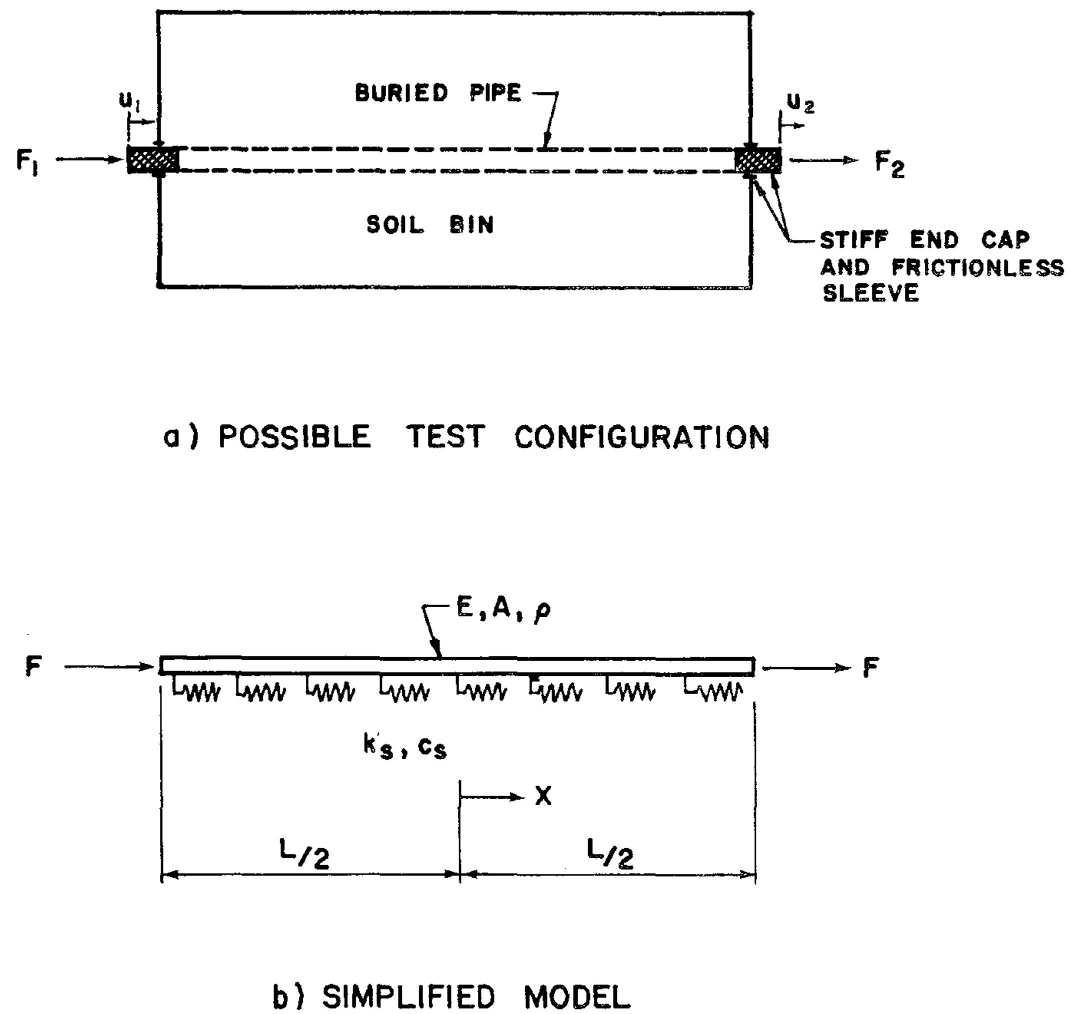


FIG. 8 POSSIBLE TEST CONFIGURATION AND SIMPLIFIED MODEL FOR BURIED CONTINUOUS PIPE - EXTENSIONAL MOTION

The equation of motion for the simplified model is:

$$\rho A\ddot{u} + c_s\dot{u} + k_s u = EA\frac{\partial^2 u}{\partial x^2}, \tag{12}$$

where u(x,t) is the pipe displacement. For the case of static loading, the $\ddot{u}$ and $\dot{u}$ terms drop out, and the solution is:

$$u = D \sinh \beta x + B \cosh \beta x, \tag{13}$$

where:

$$\beta = \sqrt{\frac{k_s}{EA}} \tag{14}$$

and where the constants D and B depend on the boundary conditions:

$$EA\left.\frac{\partial u}{\partial x}\right|_{x = L/2} = -F_1 \tag{15}$$

and:

$$EA\left.\frac{\partial u}{\partial x}\right|_{x = L/2} = F_2 \tag{16}$$

When $F_1 = F_2 = F_o$, the displacement will by symmetric (D=0) so that the displacement at either end is:

$$u_o = u(\pm L/2) = \frac{F_o}{EA\beta \tanh\frac{\beta L}{2}} \tag{17}$$

If the force deformation relation, F_o versus u_o is observed experimentally, the static soil stiffness k_s (ω=0) may be determined from Eqs (14) and (17) for each loading level F_o.

i) Dynamic Test of Buried Continuous Pipe - Extensional Motion, Test (14).

The same test configuration and model used for static tests h) may be used for the dynamic test. For the steady state, when:

$$F_1(t) = F_2(t) = F_o e^{i\omega t} \tag{18}$$

the formal solution Eq (13) still holds, but now refers only to the magnitude of u, and moreover:

$$\beta = \alpha + i\gamma = \left\{ \frac{k_s}{EA} - \frac{\omega^2 \rho}{E} - \frac{i\omega c_s}{EA} \right\}^{1/2} \tag{19}$$

in general is complex. Likewise, the solution for the end displacement, Eq (17), now includes both magnitude and a phase angle.

If the damping could be neglected, $c_s \approx 0$, β would be real for $\omega < \omega_o = \sqrt{k_s \rho / A}$. We note that as ω approaches ω_o from below, $\beta \to 0$ and Eq (17) gives:

$$\lim_{\omega \to \omega_o} u_o(\omega) = \lim_{\beta \to 0} \frac{F_o}{EA\beta \tanh\frac{\beta L}{2}} = \frac{2F_o}{EAL\beta^2} = \frac{2F_o}{Lk_s - \rho AL\omega^2} = \frac{2F_o}{k_g - m_p\omega^2}, \tag{20}$$

where $k_g = k_s L$ and $m_p = \rho AL$ is the mass of the entire buried pipe. It can be shown that the same limiting relation holds for $\omega > \omega_o = \sqrt{k_s \rho / A}$, except that now u_o will be opposite in sign from F_o, i.e., π radians out of phase. The circular frequency:

$$\omega_o = \sqrt{\frac{k_s \rho}{A}} = \sqrt{\frac{k_g}{m_p}} \tag{21}$$

thus corresponds to the natural frequency of the undamped system. For the damped system, i.e., the real system, it marks the frequency at which the phase angle crosses $\pi/2$. At that frequency, for small damping, it may be shown that:

$$u_o(\omega_o) \simeq -i \frac{2F_o}{\omega_o c_s L} . \tag{22}$$

Thus, by measuring the frequency ω_o at which the phase angle crosses $\pi/2$, a value of k_s may be obtained via Eq (21), and from the ratio $|u_o/F_o|$, c_s may be determined from Eq (22). These values apply at a given loading level. By repeating the test at a higher load level, other values may be obtained.

The tests under b) through i) represent experimentation that is of paramount importance for determining the extensional response of buried straight pipelines.

Under Phase II of the experimental program, bent pipes, thrust blocks, tee and other connections should be investigated. Specific experiments for this phase are not suggested at this time, since their design will obviously depend on the results obtained from the straight pipe experiments, as well as on continuing analytical work. Nevertheless, these results will be crucial in the analysis of pipe networks in which all these various conditions exist.

Work done by the Japanese (see Appendix A, section b) and others, [e.g., Ref. (9)], seems to indicate that the extensional effects may be an order of magnitude larger than those due to transverse effects.

Therefore, it is suggested that the current experimental program concentrate primarily on this extensional phase.

Future experimentation would then be concerned with effects from transverse motion, and twisting and buckling. Tests would be required to support this future research effort. Tests on bending, shear, and torsional deformation would, in intent, follow the same general test procedures and principles outlined in Fig. 2, for the extensional deformations, and discussed at length above. The only difference in these tests would be the types of deformation to which the pipe models would be subjected. As these tests will support future research work and do not represent a departure from the test methodologies already mentioned, it is felt that it would not be useful to elaborate further on these tests at this time.

Tests will also be needed to determine the regimes where longitudinal compression buckling or other types of instability might occur for the jointed or unjointed pipeline. As very little analytical work has been done to date to examine and define the buckling phenomena, it would be premature to discuss possible procedures for their experimentation.

The tests and variables considered above are applicable to some twenty-one different kinds of pipes, which are listed by legend in Table VI. As the task of testing all of these would be formidible without major support from the pipe manufacturers and the industry, it is suggested that the current testing program be limited to only a few of the most widely used types.

TABLE VI

Types of Pipes

Legend	Type of Pipe
CI	Cast Iron
DCI	Ductile Cast Iron
RC	Reinforced Concrete
RCC	Reinf. Conc. Cylinder
RCCP	Pretensioned Conc. Cylinder
PCC	Prestressed Conc. Cylinder
PCEC	Prestressed Conc. Embedded Cylinder
AC	Asbestos Cement
S	Steel
AL	Aluminum
W	Wood
PVC	Polyvinyl Chloride
PE	Polyethylene
ABS	Acrylonitrile Butadiene Styrene
FRP	Fiberglass Reinforced Plastic
CP	Composite Plastic (Epoxy-cased fiberglass wound over PVC liner)
TPBM	Thermoplastic Bonded Metal
RPM	Reinforced Plastic Mortar
PIC	Polymer Impregnated Concrete
CS	Corrugated Steel
FRC	Fiber Reinforced Concrete

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APPENDIX "A"

Bibliography of Completed Experimentation

This appendix provides a bibliography of references to test reports, subdivided in 12 (somewhat arbitrary) groupings, summarizing the total spectrum of completed tests. Each grouping is classified by a heading and includes a general discussion of the test reports contained in that group. The group headings and the corresponding page numbers are listed below:

a) Recent work by the Bureau of Reclamation.

The most recent experimentation by BuRec involved investigations of the behavior of the relatively new non-metallic Reinforced Plastic Mortar (RPM) and Polymer Impregnated Concrete (PIC) pipes. For the RPM pipes the laboratory program resulted in:

1) Establishing the basic properties of the pipe under conditions of hydrostatic loading, fatigue, creep and crushing.
2) Determining the scaling effect introduced by changes in pipe diameter.
3) Determining the stiffness dependence of the pipe on ovalling and aging.
4) Determining the ring stiffness of the buried pipe in compacted soil.

For the PIC pipes, experimentation consisted in hydrostatic and three-edge-bearing tests. Laboratory tests were conducted to investigate the behavior of different kinds of flexible pipes under three-edge-bearing loads and surcharge loads in a soil box container. These static tests were performed on Fiberglass Reinforced Plastic pipes (FRP), Polyethylene pipes (PE), Polyvinyl Chloride pipes (PVC), and Steel pipes. The initial work was done on Steel pipes buried in a low-density cohesive soil, and then extended to Steel pipes in a high-density cohesive soil and to FRP, PE and PVC pipes buried in low density lean clay backfills. Tests were then performed on steel, RPM and FRP pipes buried in sand backfills. The cohesive backfill materials in these tests was compacted to either 90 or 100 percent of Proctor to give both a low and high modulus stiffness condition.

BUREAU OF RECLAMATION PUBLISHED REPORTS

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b) Recent work done in Japan.

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The Ministry of Transport in the period between April, 1974 and September, 1976, recorded the relative displacements along a 2,500 meter long straight pipeline, through the use of a horizontal seismometer array having six recording stations. Thirty five earthquake events were recorded, of which six have been analyzed, (see ref. 2). The Sagamihara Research and Engineering Center of the Nippon Steel Corp. (see ref. 4) has compared seismic response measurements made on an in-situ bellows-type jointed pipeline during 1975 with the response predicted by analytical methods. Kobe University conducted experiments in 1975, under the supervision of Nogao and Takada, to determine the pipe slippage effect and the non-linear frictional forces between pipe and soil, (see ref 5.) In these experiments, the longitudinal frictional restoring force was measured as a function of extensional displacement for static and shake table harmonic loadings under various earth surcharge pressures. This testing program involved the monitoring of the responses of about 100 different jointed steel and cast iron pipe models. The joints in these models were rubber-gasketed mechanical joints spaced at 5 and 6 meters, respectively. Experimental studies of travelling wave effects on the response of buried steel pipelines under three kinds of dynamic loadings were investigated by Kubo in 1973 (see ref. 9.). The travelling waves were generated by dynamic explosions, S-wave generators and air-gun blasts. The Japanese have also performed a considerable amount of work in regard to submerged tunnels. Since 1970 measurements of the significant strains and accelerations occurring at the Haneda Tunnel during seismic events have been taken. This tunnel, under the Tama River, is 480 meters long, slightly upstream from Tokyo International Airport. Records of some thirty earthquakes have been evaluated by the Institute of Industrial Science at Tokyo University, under the supervision of Tamura (see ref. 3 & 15). The Institute also conducted model vibration tests of submerged tunnels buried in the surface ground layer.

Many researchers have contributed experimental work evaluating the seismic response of submerged tunnels using either full scale tunnels or models. (For a listing of these, see ref. 11 through 1.9) One of the most recent tunnel studies performed by Goto in 1973, (see ref. 11) used a rubber model embedded in a gelatin - like material, which represented the surrounding soil and which was shaken by a shake table. A study of the seismic measurements on existing pipelines from the earthquake swarm near Matsushiro, Japan between 1965 and 1967 was performed by Sakurai and Takahaski (see Ref. 20 & 21).

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e) Performance of Buried Pipes and Culverts

Experiments on the behavior and performance of both rigid and flexible conduits have been conducted at the Iowa State Engineering Experiment Station at Ames, Iowa over the past 65 years. These studies were primarily concerned with the ring behavior of the pipes and the distribution of contact soil pressures at the pipe-soil interface and in the surrounding soil. This work was largely done under the direction of Professors M.G. Spangler, A. Marston and W.J. Schlick (see ref. 1-14). Other work on the deformation of flexible pipe culverts was performed at the Utah State Engineering Experiment Station under the guidance of Professors R.K. Watkins and F.D. Nielson, (see ref. 15, 16, 18 & 20). Spangler also conducted a long term experiment to measure the settlements of culverts of concrete, cast iron, and corrugated steel over a period of 21 years (see ref.19).

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13. Barnard, R.E. - Design and Deflection Control of Buried Steel Pipe Supporting Earth Loads and Live Loads Proc. ASTM 57:1233, 1957.

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15. Watkins, R.K. - Influence of Soil Characteristics on Deformation of Embedded Flexible Pipe Culvert, Bulletin 223, Highway Research Board, 1959.

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f) Recent Hydrostatic and Waterhammer Tests

Recent experimentation on surge pressure effects were aimed at determining the response of the pipe as a function of the tensile modulus of elasticity of its material.

1. Glascock, B.C., "Hydrostatic Design Basis for Techite RPM Type I Pressure Pipe," Technical Report No. ER-01033, Rev. B, Amoco Reinforced Plastics Company, Riverside, California, 1974.

2. Plastics Pipes Institute - The Nature of Hydrostatic Time-to-Rupture Plots, PPI Technical Note PPI-TN7, New York, N.Y., Sept. 1973.

3. Flammer, G.H., Jeppson, R.W., and Watters, G.Z. - Experimental Study of Water Hammer in Buried PVC and Permastran Pipes - Utah Water Research Laboratory, Utah State University, Logan, Utah, April, 1972.

4. Maahs, A.J., - Water Hammer Allowances - Asbestos Cement Pipe, AWWA Journal, November, 1952.

g) Gasketed Bell-and Spigot Joints

Recent tests on the rubber-gasketed Bell-and Spigot type joints have been directed towards determining the leakage and failure limits of these joints (see ref. 1 & 2). There has been no full scale testing to measure the contact pressures and friction between gasket and pipe as a function of the internal pressure and the applied static loads. However, in 1967 Valenziano of the Interpace Corporation, conducted tests on scaled down plexiglass joint models, in which he measured the gasket contact pressures as a function of hydrostatic pressure (see ref. 3). In 1935, Prior did tests on the Bell-and-Spigot joints in cast iron pipes, which provide some useful information on joint elongation and rotation, but these were long term tests including creep relaxation, and were done only on non-pressurized pipes.

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2. Robertson, G.G., Determining Pressure Sealing Capacity of Pipe Gaskets, Journal of the American Waterworks, Vol. 61, No. 7, July, 1969. American Water Works Association, 6666 West Quincy Avenue, Denver, Colorado 80235.

3. Valenziano, F.P., Rubber Gaskets Joints for Concrete Pipe - Journal of AWWA, November, 1967, American Water Works Association, 6666 West Quincy Avenue, Denver, Colorado 80235.

4. Prior, J.C., "Investigation of Bell-and-Spigot Joints in Cast-Iron Water Pipes", Engineering Experiment Station Bulletin 87, January 1935, Ohio State University.

h) Buckling in a Soil Medium

The critical ring buckling loads for flexible pipes buried in a sand medium were investigated by Allgood, Chelapati and Luscher, (see ref. 1 & 2), who showed that, in some cases the critical so-called energy load (see ref. 5) is significantly different from the Euler load. The Applied Research Laboratory of the U.S. Steel Corp. has conducted, under the supervision of Charles G. Schilling, an investigation into the buckling strength of circular steel tubes in an air medium and have shown that their strength is a function of the particular fabrication process used, and most essentially, of the initial imperfections (see ref. 3). The case of buckling of long cylindrical shells was also investigated by Forrestal and Herrmann and discussed in 1964 (see ref. 4).

1. Allgood, J.R. and Chelapati, C.V.-Buckling of Cylinders in a Confining Medium,Highway Research Record 413, 1972.

2. Luscher, V. - Buckling of Soil Surrounded Tubes, Journal of the Soil Mechanics and Foundation Division, ASCE Vo. 92, No. SM6 Proc. Paper 4990,Nov. 1966.

3. Schilling, C.G. - Buckling Strength of Circular Tubes - Proc. Paper 4520, Journal of the Structural Division, ASCE Vol. 91 No. ST5, Oct. 1965.

4. Forrestal, M.J. and Herrmann, G., -Buckling of a Long Cylindrical Shell Surrounded by an Elästic Medium Presented at ASCE Structural Engr. Conf. Preprint 108, Oct. 1964.

5. Friedrieks, K.O. - On the Minimum Buckling Load for Spherical Shells California Institute of Technology, Theodore Von Karmon Anniversary Vol. p 258-272, 1941.

i) Tube Bending

The American Institute of Steel Construction has recently sponsored a research project to investigate the ultimate plastic capacity in an air of circular steel tubes in bending. These tests were done under supervision of Professor D.R. Sherman of the University of Wisconsin (see ref 1-4).

1. Sherman D.R. - Tests of Circular Steel Tubes in Bending - discussion closure, Journal of the Structural Division ASCE Vol. 104 No. ST2, Feb. 1978.

2. Sherman D.R. - Tests of Circular Steel Tubes in Bending, Journal of the Structural Division ASCE Vol. 102 No. ST 11, Nov. 1976.

3. Sherman D.R. - Circular Steel Tubes in Bending Preprint 2694 ASCE National Water Resources and Ocean Engineering Convention, San Diego, California, April 1976.

4. Glass, A.M. and Sherman D.R. - Bending Capacity of Circular Tubes Proceedings Offshore Technology Conference, paper 2119, May 1974.

j) Forces on Cylinders

The U.S. Naval Civil Engineering Laboratory at Port Hueneme, California has studied, under the supervision of J.R. Allgood, the static behavior of a horizontally oriented concrete cylinder model in sand (without internal pressure), (see ref. 1 and 2). The Waterways Experiment Station at Vicksburg, Mississippi has studied the static and dynamic response of buried cylinder pipe models in sand (see ref. 3 and 4). The National Science Foundation sponsored work at Brown University, aimed at determining the plastic limit of cylindrical shells under ring loads.

Work was done on unpressurized, unjointed steel and aluminum cylinders and was conducted by H.H. Demir, in 1964-1965 (see ref. 5). Augusti and D'Agostino, under a grant from the National Research Council of Italy, performed tests on fixed-ended mild steel cylinders, subject to uniform radial pressure. The purpose of these tests was to investigate their non-linear plastic behavior, and to establish the ultimate strength of the shells (see ref. 6). The behavior of the pressurized cylinders under concentrated and line load forces has been studied by Bijlaard (see ref. 7-9).

1. Allgood, J.R., and Herrmann, H.G., III. Static Behavior of Buried Reinforced-Concrete Model Cylinders. U.S. Naval Civil Eng. Laboratory, Port Hueneme, California, Tech. Rept. R-606, Jan. 1969.

2. Allgood, J.R., Ciani, J.B., and Lew, T.K.,-Influence of Soil Modulus on the Behavior of Cylinders Buried in Sand,U.S. Naval Civil Engr. Laboratory, Port Hueneme, California, Tech. Rept. R-582 June 1968

3. Albritton, G.E.,-Behavior of Flexible Cylinders Buried in Sand Under Static and Dynamic Loading,Waterways Exp. Sta., Vicksburg Miss. Rept. 1-821,April 1968

4. Dorris, A.F.,-Response of Horizontally Oriented Buried Cylinders to Static and Dynamic Loading. Waterways Exp. Sta., Vicksburg, Mississippi, Tech. Rept. 1-682, July 1965.

5. Demir, H.H. -Cylindrical Shells under Ring loads, Journal of Structural Division, ASCE, Vol. 91, No. ST3, June, 1965.

6. Augusti, G. and D'Agostino, S. - Tests of Cylindrical Shells in the Plastic Range Journal of the Engineering Mechanics Division, ASCE, Vol. 90, No. EM1, Proceeding Paper 3802, February, 1964.

7. Bijlaard, P.P. - Additional Data on Stresses in Cylindrical Shells Under Local Loading - Welding Research Council Bulletin, No. 50, May, 1959.

8. Bijlaard, P.P. - Stresses from Radial Loads and External Moments in Cylindrical Pressure Vessels - Welding Journal, Volume 34, December 1955.

9. Bijlaard, P.P. - Stresses from Local Loadings in Cylindrical Pressure Vessels - Transactions, American Society of Mechanical Engineers, Volume 77, No. 6, August, 1955.

k) Branched Connection Behavior

From 1969 on, the elasto-plastic behavior of branched tee pipe connections has been studied on pressurized steel models. This work was sponsored jointly by the Pressure Vessel Research Committee U.S.A., and the National Research Council of Canada (Grant 3803) (see ref. 1). Experiments, which determined the flexibilities and plastic limits of pipe elbows, branch laterals and tee connections were discussed at the Second International Conference for Pressure Vessel Technology in San Antonio Texas in 1973, (see ref. 2-4).

1. Ellyin F. - An Experimental Study of Elasto-Plastic Response of Branch-Pipe Tee Connections Subjected to Internal Pressure, External Couples and Combined Loadings - Welding Research Council Bulletin 230, September 1977, Welding Research Council, 345 East 47th Street, New York, New York 10017.

2. Findlay, F.E. and Spence J. - Limit Loads for Pipe Bends Under In-Plane Bending - Second International Conference on Pressure Vessel Technology 1-Design and Analysis, San Antonio, Texas, Oct. 1973.

3. Imamasa, J. and Uragami,K., "Experimental Study of Flexibility Factors and Stresses of Welding Elbows and End Effects", Second International Conference on Pressure Vessel Technology Part 1 Design and Analysis, San Antonio, Texas, October 1973.

4. Gartenburg, J., Schroeder, J. and Srinivasaian, K.R., "Limit Interaction of External Couples and Internal Pressure for Branch-Pipe Lateral and Tee Connections - Part II, Theoretical and Experimental Results for In-Plane and Out of Plane Limit Couples Applied to the Branch and their Interaction with Pressures". Second International Conference on Pressure Vessel Technology,Part 1-Design and Analysis, San Antonio, Texas.

1) Behavior of Buried Pipes under Horizontal and Vibratory Motions

Woodward-Clyde Consultants and Geotechnical Engineers Inc. jointly conducted model tests on a pipe buried in a testing box filled with sand and subject to translational forces. The purpose of these tests was to study the soil-pipe interaction as a function of depth of burial, pipe diameter and soil density (see ref. 1). The University of Western Ontario has conducted full scale tests on buried reinforced concrete, non-pressurized pipes to study the effects of vertical vibratory compaction (see ref. 2). These tests were sponsored by the Ontario Concrete Pipe Association and the National Research Council of Canada.

1. Audibert, J.M., and Nyman, K.J. - Soil Restraint Against Horizontal Motion of Pipes - Proceeding of the ASCE - Journal of the Geotechnical Engineering Division Vol. 103 No GT10, Oct. 1977.

2. Hindy, A., Novak, M., and Poucher, M.P. -Effect of Vibratory Compactors on Buried Concrete Pipe - Report GEOT-2-76 U. of Western Ontario, Faculty of Engineering Science, London, Ontario, Canada 1976.

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