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Overall aims of this research are to develop a systematic way of assessing the adequacy and vulnerability of water/sewer distribution systems subjected to seismic loads and to develop future design methodologies. To aid in the design of buried pipelines against earthquakes, this paper evaluates the reserve strength of buried pipes beyond normal stress/strain conditions. This reserve strength is the capacity available in buried pipes to resist seismic loads. In buried pipelines under combined conventional and seismic loadings, bi-axial stresses are developed since conventional loads produce mainly hoop stresses whereas the seismic effect is predominantly in the longitudinal direction. To evaluate the failure of buried pipelines consisting of non-homogeneous materials under a bi-axial stress state, a modified Von-Mises failure criterion is proposed. This paper evaluates parametrically the reserve strengths of a typical cast iron (rigid) pipe and a typical ductile iron (flexible) pipe with several important parameters such as aging (corrosion effect), laying and loading conditions, buried depth, dynamic effect, and trench load uncertainty factor in estimating vertical earth and truck loads. It is concluded that the seismic reserve axial strength of buried pipes is influenced by all the parameters investigated. The effects from corrosion, loading condition, and trench load uncertainty factor are more pronounced than those from buried depth, laying condition, and the earthquake induced dynamic water pressure effects.

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# Seismic Vulnerability, Behavior and Design
# of Underground Piping Systems

## Seismic Design Criteria
## For Buried Pipelines *

by

Leon Ru-Liang Wang
Raymond Chong-Yu Fung

Sponsored by National Science Foundation
Directorate for Applied Science and Research Application (ASRA)

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Technical Report (SVBDUPS Project) No. 8

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The authors wish to express their appreciation for the inputs and discussions from all members of the research team during the course of investigation.

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# SEISMIC DESIGN CRITERIA FOR BURIED PIPELINES

by Leon Ru-Liang Wang and Raymond Chong-Yu Fung

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Soil-structure Interaction

# SEISMIC DESIGN CRITERIA FOR BURIED PIPELINES

by Leon Ru-Liang Wang[1], M. ASCE and Raymond Chong-Yu Fung[2]

## ABSTRACT

To aid in the design of buried pipelines against earthquakes, this paper evaluates the reserve strength of buried pipes beyond normal stress/strain conditions. This reserve strength is the capacity available in buried pipes to resist seismic loads. In buried pipelines under combined conventional and seismic loadings, bi-axial stresses are developed since conventional loads produce mainly hoop stresses whereas the seismic effect is predominantly in the longitudinal direction. To evaluate the failure of buried pipelines consisting of non-homogeneous materials (cast iron, concrete, etc.) under a bi-axial stress state, a modified Von Mises failure criterion is proposed.

For practical applications, this paper evaluates parametrically the reserve strengths of a typical cast iron (rigid) pipe and a typical ductile iron (flexible) pipe with several important parameters such as aging (corrosion effect), laying and loading conditions, buried depth, dynamic effect (earthquake induced water pressure) and trench load uncertainty factor in estimating vertical earth and truck loads. It is concluded that the seismic reserve axial strength of buried pipes is influenced by all the parameters investigated. The effects from corrosion, loading condition and trench load uncertainty factor are more pronounced than those from buried depth, laying condition and the earthquake induced dynamic water pressure effects.

## INTRODUCTION

The current design practice (1,2) for water/sewer lifelines does not take seismic loads into account. However, recent studies (3,4,9,10, 18) have shown that buried gas, water/sewer pipelines have been damaged heavily by earthquakes. Because of the importance of lifelines to the health and safety of the populace, lifeline earthquake engineering is beginning to draw the attention of the engineering profession (8,25,26). Recently, seismic response behavior (8,15,24) has been studied and design considerations (5,20) have been discussed.

For evaluation of existing piping systems as well as future design applications, this paper proposes a modified Von Mises failure criterion

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to evaluate the safety of buried pipelines. The study defines the reserve strength of a buried pipeline beyond its normal stress/strain conditions. This reserve strength/ductility is the capacity available to resist seismic loads. By comparing the reserve strains/curvatures with the imposed ground strains/curvatures, the safety of a given pipeline can be investigated.

The normal loads for the non-seismic design are internal operating and surge pressures (for water pipes), trench loads from earth, truck and impact. Based on plane stress-strain assumptions, these loads produce only ring tension (from internal pressures) and ring bending (from uniformly distributed trench loads) in the buried pipe. The effects of locally concentrated load which may produce longitudinal bending and the effects of internal pressure at closed ends which may produce axial stresses have not been considered in the conventional non-seismic design.

On the other hand, recent seismic investigations (11,13,14,19) have indicated that buried pipelines and submerged tunnels closely follow the ground movement in both longitudinal and lateral directions during seismic shaking. The axial (longitudinal) stresses/strains in buried pipelines were found to be predominant in all cases. Thus, the seismic design criteria for buried pipelines must include the effects of combined stress/strain in both hoop and longitudinal directions.

In the design of buried pipelines, a corrosion tolerance is added to the required thickness. With the passing of time, the corrosion tolerance thickness is reduced. Thus, the reserve strength/ductility calculated for seismic resistance will also vary with time.

To aid in the design of buried pipelines against earthquakes, this paper presents the reserve strength/ductility characteristics of common cast iron and ductile iron pipes of various dimensions and thicknesses under a variety of buried depth/laying conditions. The pipeline under investigation is assumed to be continuous, thus eliminating the effect of joints.

## CONVENTIONAL NON-SEISMIC DESIGN

### General Discussions

The conventional methods used for determining the loads on buried pipes can be attributed to the early works of Marston (12), Schlick (21) and Spangler (22). Based on these and other developments, the AWWA standards (1,2) are written. The analysis/design of buried pipes are divided into two categories, namely flexible and rigid types, using two essentially independent methods. The separation is based on the relative stiffness of the pipe and the surrounding soil. In most cases, the thickness determines the characteristics (rigid or flexible) of the pipe.

Separate analyses are used for rigid pipes (such as concrete or cast iron) and for flexible pipes (such as ductile iron and steel). For rigid pipe design, the deflection of the pipe is assumed to be so small that the lateral soil resistance does not play a significant role in the analysis. Thus, the ring stresses in the pipe come from the combination of internal water pressure and external earth and/or truck loads. For flexible pipes, the lateral resistance of the soil is a major design factor because of the pipe's relatively large lateral deflection characteristics. Due to the fact that the vertical deflection of the pipe will reduce the vertical trench load, while the horizontal deflection will increase the soil resistance, the AWWA design method (2) is based on a stress produced either by the internal water pressure or by the external trench loads, but not the combination of both as in the rigid pipe design.

The magnitude of the trench load from the earth and truck etc. transferred to the buried pipe depends on the buried depth and the laying condition. For example, the AWWA defines three laying conditions for cast iron pipe design and five laying conditions for ductile iron pipe design.

Most buried water/sewer pipes consist of non-linear, non-homogeneous materials, such as cast iron, ductile iron and concrete. The capacities of these materials are represented by a uniaxial (tensile or compressive) strength and a modulus of rupture or bending strength. In general, the safety of a buried pipe needs to be checked against both strengths. For rigid pipe design, the failure from combined stresses (ring tension and ring bending) is determined by an interaction equation.

Finally, the conventional design of buried pipes takes the aging effect into account. From current AWWA Codes, the corrosion allowance added to the design wall thickness ranges from 0.05 inches to 0.10 inches depending on pipe material and size. Based on a 30 year life, this paper assumes that the reduction of wall thickness by corrosion will be 0.03 inches for every 10 years.

## Conventional Non-Seismic Stress Analysis for Cast Iron Pipes

The design for cast iron pipe is typical of "rigid" pipe design. Figure 1 shows a conventional rigid pipe design flow chart. The design is controlled by one of two loading conditions. Loading Condition #1 includes the earth pressure (without truck load) plus working and surge water pressures. Loading Condition #2 considers earth pressure, traffic and impact loads plus operating water pressure (without surge). With the inclusion of the corrosion and manufacturing allowances, the safety factor for an initially designed pipe is always greater than 2.5.

According to published research results from Iowa State University (12,21,22), the ring bending stress, $\sigma_{b,r}$, due to an equivalent vertical load, W, is:

$$\sigma_{b,r} = 0.0795W\ (d+t)/t^2 \quad \text{(psi)} \tag{1}$$

where d = nominal diameter of pipe (in.)
t = thickness of pipe (in.)
W = equivalent vertical trench load (lbs/lin ft)

W is an equivalent test loading (lbs/lin.ft) from vertical earth and traffic loads and is a function of laying condition and buried depth.

The ring tension produced by the internal pressure, $\sigma_{t,r}$ is:

$$\sigma_{t,r} = p\ d/2t \tag{2}$$

where p is internal water pressure with or without surge.

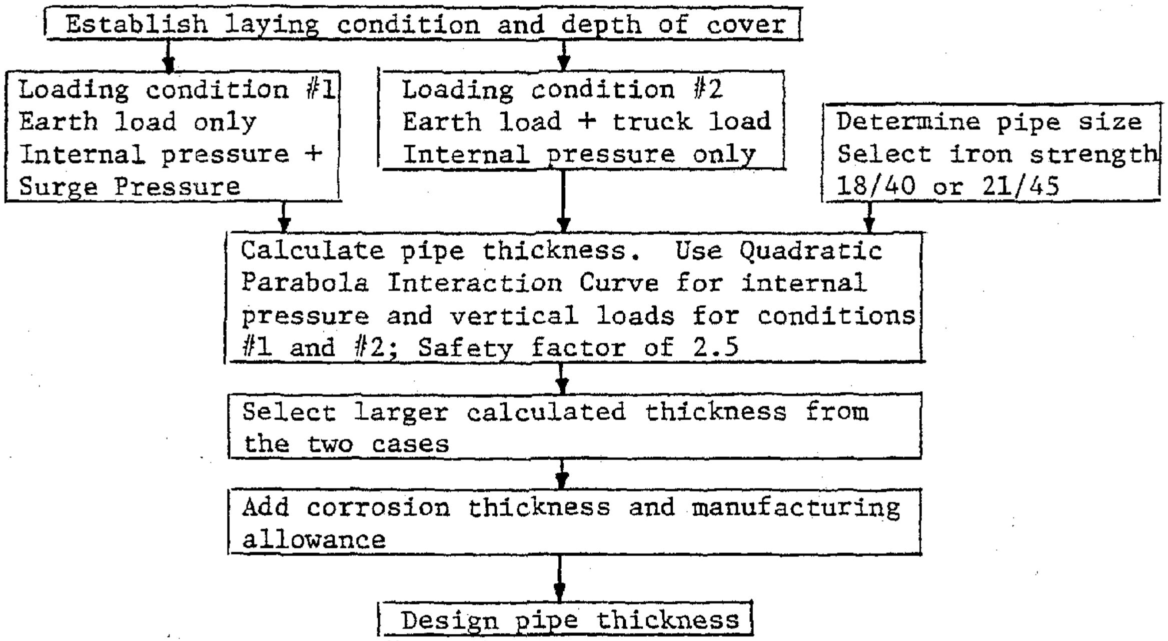

FIG. 1 RIGID PIPE DESIGN METHOD FOR CAST IRON PIPES

The combined stress in the buried pipe, $\sigma_{c,r}$, is the sum of ring bending and ring tension:

$$\sigma_{c,r} = \frac{p\ d}{2\ t} + \frac{0.0795\ W(d+t)}{t^2} \tag{3}$$

The tensile strength, $\sigma_{ty}$ of the material may be used to check the ring tension (Eqn. 2) and the modulus of rupture, $\sigma_{by}$ may be used to check the combined stress (Eqn. 3). However, for the combined effect of ring tension and bending for the non-homogeneous cast iron material, the AWWA (1) presents a quadratic parabola interaction equation as its failure criterion. Thus, for a given ring tensile stress, $\sigma_{t,r}$, the reduced modulus of rupture, $\bar{\sigma}_{by}$, is specified as:

$$\bar{\sigma}_{by} = \sigma_{by} \sqrt{1 - \sigma_{t,r}/\sigma_{ty}} \tag{4}$$

and should be used to check the combined stress. In other words, the non-seismic safety factor for buried rigid pipes is:

$$(S.F.) = \sigma_{c,r}/\bar{\sigma}_{by} \tag{5}$$

Recently, Parmelee (16) indicated that these conventional calculated stresses might be different from the measured stresses by a multiple of 4 or 5 times either way. To account for such variations, a trench load uncertainty factor, $\alpha$, will be used to modify the standard calculated stresses due to the vertical trench load from earth, truck and impact.

## Conventional Non-Seismic Stress Analysis for Ductile Iron Pipes

The design for ductile iron pipe is typical of "flexible" pipe design. Figure 2 shows the flow chart for the conventional flexible pipe design. As shown in Fig. 2, the design of flexible pipe is controlled by three criteria, namely, (i) the internal water pressure (operating and surge pressure), (ii) trench loads from earth, truck and impact and (iii) pipe deflection.

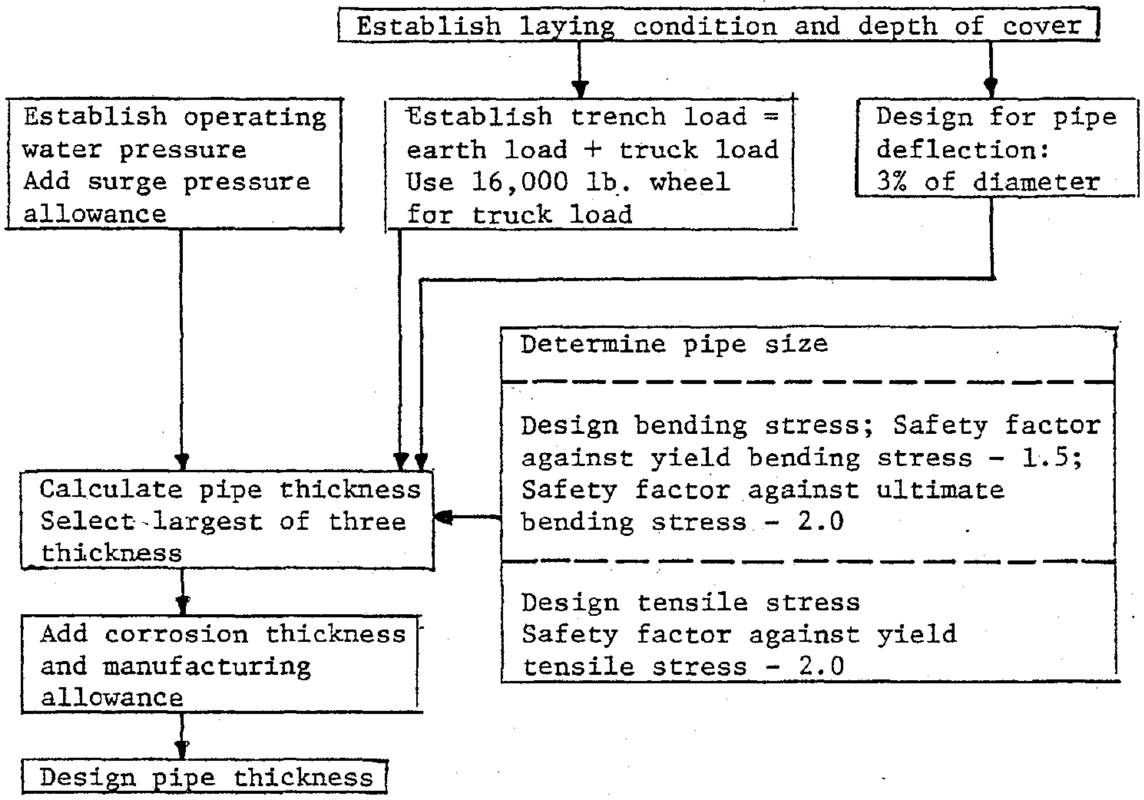

FIG. 2 FLEXIBLE PIPE DESIGN METHOD FOR DUCTILE IRON PIPES

The ring tension due to internal pressure is given by Eqn. (2). The ring bending produced by the equivalent vertical trench load as suggested by Iowa State University research (2) is:

$$\sigma_{b,r} = 3\,P_v \frac{d_o}{t}\left(\frac{d_o}{t} - 1\right)\left[k_b - \frac{k_x}{\dfrac{8E}{E'\left(\dfrac{d_o}{t} - 1\right)^3} + 0.732}\right] \text{ (psi)} \qquad (6)$$

where $d_o$ = Outside diameter of pipe (in)
$E$ = Young's modulus of pipe (psi)
$E'$ = Modulus of soil reaction (psi)
$k_b$ = Bending moment coefficient
$k_x$ = Deflection coefficient
$P_v$ = Equivalent vertical trench load (psi)

Note that $P_v$ is a function of buried depth and $E'$, $k_b$ and $k_x$ depend on the laying condition.

In flexible pipe design, the tensile strength of the material is used to check the ring tension and the bending strength is to check the ring bending. As discussed earlier, no interaction of stress is necessary. Thus, the non-seismic safety factor for buried flexible pipes will be

$$(S.F.) = \sigma_{t,r}/\sigma_{ty} \text{ or } \sigma_{b,r}/\sigma_{by} \tag{7}$$

Similarly to the rigid pipe design, a load adjustment factor, $\alpha$, is used in this paper to study the uncertainty effect from the vertical trench (earth, truck and impact) loads.

## ADDITIONAL STRESSES IN BURIED PIPES

### General Discussions

The conventional plane stress/strain non-seismic stress analyses only give the ring tension and ring bending stresses. However, for seismic resistance, the axial (longitudinal) strength of buried pipes is most important (8,11,14,15,24). Following are additional stresses which have not been considered in the conventional analyses.

### Longitudinal Stress Due to Partial Live Load

Based on the theory of beams on elastic foundation (7), the longitudinal bending stress, $\sigma_{b,L}$, in the pipeline due to partially distributed truck and impact loads is found to be:

$$\sigma_{b,L} = \frac{wd}{2I} \sqrt{\frac{EI}{\lambda}} \tag{8}$$

where $I$ = Moment of inertia pipe
$w$ = imposed live load
$\lambda$ = Spring constant for lateral soil resistance

### Axial Stress Due to Internal Pressure

When a buried pipe comes to a closed end or directional change, local axial stress due to internal pressure, $\sigma_{a,L}$, developes (23) as:

$$\sigma_{a,L} = p\, d/4\, t \tag{9}$$

This stress diminishes in the longitudinal direction of the pipe since the axial force generated by the internal pressure will be resisted by the soil friction around the pipe. However, for seismic resistance evaluation, this local axial stress should be included in the analysis.

### Dynamic Effect Due to Seismic Excitation

The conventional stress analysis is for static loads only. However, under a seismic excitation, there may be a dynamic effect that will increase the internal water and surge pressures. To account for this effect, this paper assigns a dynamic load factor, $\beta$, ranging from 1 to 2, to the internal water pressure and surge pressure. The investigation of the true dynamic factor for various earthquakes is out of the scope of this paper.

## SEISMIC RESERVE STRENGTH OF BURIED PIPES

### Stresses and Strengths

The biaxial stresses on a buried pipe element subjected to both seismic and conventional non-seismic loads are shown in Fig. 3 in which $\sigma_1$, $\sigma_2$ are the stresses in the longitudinal and hoop direction respectively.

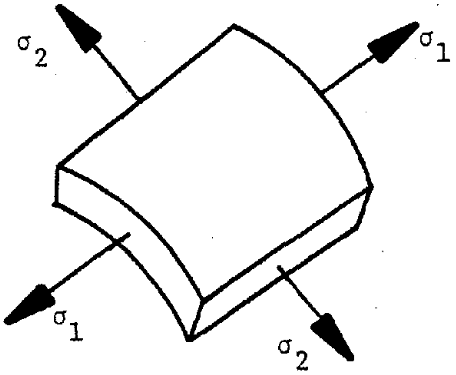

FIG. 3 STRESSES IN A BURIED PIPE ELEMENT

Since the axial stress during earthquakes has been shown to be predominant, the seismic bending effect is neglected. Thus, this paper developes the seismic reserve strength of buried pipes in the longitudinal direction only.

The calculated stress, $\sigma_1$, for combined seismic and non-seismic effects in the longitudinal direction is:

$$\sigma_1 = \sigma_{as} + \beta\,\sigma_{a,L} \pm \alpha\,\sigma_{b,L} \qquad (10)$$

where $\sigma_{as}$ is the seismic axial stress produced by an earthquake in the longitudinal direction.

For the evaluation of the safety of buried pipes against earthquakes, $\sigma_{as}$ is the required seismic reserve strength which may be used as the seismic design criteria for buried pipes.

Since Eqn. (10) represents a combined axial and bending stress condition, the tensile strength according to the quadratic parabola interaction (1) in the longitudinal direction, $\sigma_{1y}$, will be:

$$\sigma_{1y} = \sigma_{ty}\,[1 - (\frac{\alpha\sigma_{b,L}}{\sigma_{by}})^2\,] \qquad (11)$$

Depending on the pipe constructions, the total (seismic plus non-seismic) hoop stress, $\sigma_2$, is calculated as follows:

$$\sigma_2 = \beta\,\sigma_{t,r} \pm \alpha\,\sigma_{b,r} \qquad (12)$$

for the rigid pipes and

$$\sigma_2 = \beta\ \sigma_{t,r} \tag{13a}$$

or

$$\sigma_2 = \alpha\ \sigma_{b,r} \tag{13b}$$

for the flexible pipes.

Note that for flexible pipe design, either ring tension or ring bending may control, the available strength, $\sigma_{2y}$, will either be $\sigma_{ty}$ or $\sigma_{by}$ depending on which type of stress controls. However, for rigid pipe design, the stresses (tension and bending) are combined and the available strength in hoop direction will be obtained by modifying Eqn. (4).

$$\sigma_{2y} = \sigma_{by} \sqrt{1 - \beta\sigma_{t,r}/\sigma_{ty}} \tag{14}$$

## Modified Von Mises Criteria

For homogeneous materials, the Von Mises yield criteria (17) has been developed to define the failure of an element under a biaxial stress state as:

$$\frac{(\sigma_1 - \sigma_2)^2}{2} + \frac{\sigma_1^2}{2} + \frac{\sigma_2^2}{2} = \sigma_y^2 \tag{15}$$

which may be rewritten as:

$$\left(\frac{\sigma_1}{\sigma_y} - \frac{\sigma_2}{\sigma_y}\right)^2 + \left(\frac{\sigma_1}{\sigma_y}\right)^2 + \left(\frac{\sigma_2}{\sigma_y}\right)^2 = 2 \tag{16}$$

However, for buried cast-iron or ductile iron pipe, the material is not homogeneous and Eqn. (15) and Eqn. (16) do not apply. For design purposes, this paper proposes a "modified" Von Mises failure criterion to include the non-homogeneous characteristics of material as follows:

$$\left(\frac{\sigma_1}{\sigma_{1y}} - \frac{\sigma_2}{\sigma_{2y}}\right)^2 + \left(\frac{\sigma_1}{\sigma_{1y}}\right)^2 + \left(\frac{\sigma_2}{\sigma_{2y}}\right)^2 = 2 \tag{17}$$

where $\sigma_{1y}$ and $\sigma_{2y}$ are the yield strengths in 1 and 2 direction respectively.

Substituting the calculated stresses and available strengths developed in Eqns. (10) thru (14) into Eqn. (17), the seismic reserve strength $\sigma_{as}$ of a buried pipe beyond its normal stress condition can be readily determined.

## PARAMETRIC STUDIES

To aid the future seismic design of buried pipelines, this paper examines the effects of a number of important parameters such as thickness, aging (corrosion), loading condition, laying condition, uncertainty factor on trench loads, and dynamic effect on water pressure, on the seismic reserve strengths. The initial design thickness is based on the standard AWWA Specifications (1,2). Following are separate discussions on a typical cast-iron (rigid) pipe and a typical ductile iron (flexible) pipe.

Cast Iron Pipe (Rigid)

As an example for the parametric study, a cast iron pipe with the following data is used:

Nominal diameter, $d = 18$ in (46 cm)
Tensile strength, $\sigma_{ty} = 18$ ksi (124 MPa)
Modulus of Rupture, $\sigma_{by} = 40$ ksi (276 MPa)
Operating Water pressure, $p_o = 200$ psi (1380 KPa)
Surge pressure, $p_s = 100$ psi (690 KPa)
Buried depth, $h = 5$ ft (1.5 m)
Initial safety factor, (S.F.) = 2.5

For cast-iron pipe construction, AWWA (1) suggests three possible laying conditions as noted below. In this paper, Laying Condition B is chosen as the standard case.

| Laying Condition | Description |
|---|---|
| A | Pipe laid on flat bottom trench, backfill not tamped |
| B | Pipe laid on flat bottom trench, backfill tamped |
| F | Pipe bedded in gravel or sand, backfill tamped |

The design of cast-iron pipe is controlled by one of the two possible loading conditions listed:

| Loading Condition | Description |
|---|---|
| # 1 | Operating water and surge pressure + earth load (No live loads) |
| # 2 | Operating water pressure + earth and live loads (No surge pressure) |

In this paper, stresses under both loading conditions are calculated but only the critical results are presented.

Following the AWWA specification (1), the initial design is found to be controlled by Loading Condition # 1 and the thickness is 0.47 in (1.19 cm). With an 0.08 in (0.20 cm) corrosion allowance and a 0.08 in (0.20 cm) manufacturing allowance added, the initial design thickness becomes 0.63 in (1.60 cm) and AWWA Class # 23 pipe is designated.

Using the proposed "modified" Von Mises failure criterion, the effects of corrosion and thickness on the reserve axial strength under conventional Loading Condition # 2 is shown in Fig. 4 with an 'age' parameter shown by T = 0, 20, 40, 60 and 80 years of life. Although the initial non-seismic design is controlled by Loading Condition # 1, the effect of axial stress produced by the live loads (truck + impact) which have not been considered in the conventional design greatly reduces the seismic factor for the seismic reserve strength.

The effect of laying condition on the reserve axial strength is shown in Fig. 5. From this figure, one can conclude that the reserved strength is a function of surrounding soil stiffness.

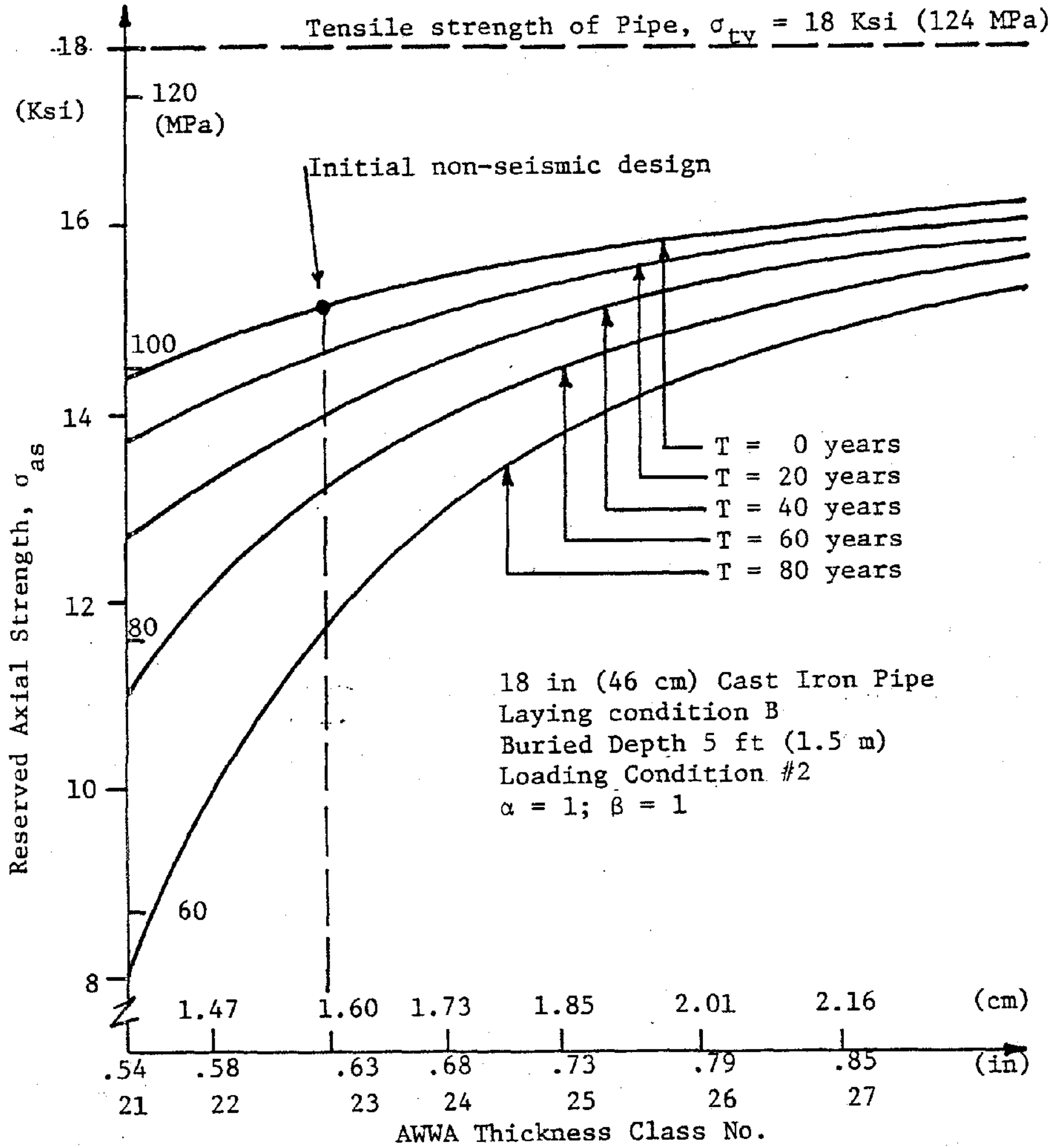

FIG. 4 RESERVED AXIAL STRENGTH VS. THICKNESS

Figure 6 shows the effect of the trench load uncertainty factor to the vertical loads predicted by the Iowa formulas (12,21,22). This figure indicates that when $\alpha > 1$, the reserve strength is greatly reduced. Thus in actual design, one must be careful to select a reasonable $\alpha$ value.

The effects of buried depth and dynamic water pressure will be presented in a subsequent report (6).

In conclusion, the seismic reserve axial strength of buried cast-iron pipe is influenced by all parameters investigated. The effects from corrosion, loading condition and the trench load uncertainty factor are more pronounced than those from buried depth, laying condition and dynamic load factor.

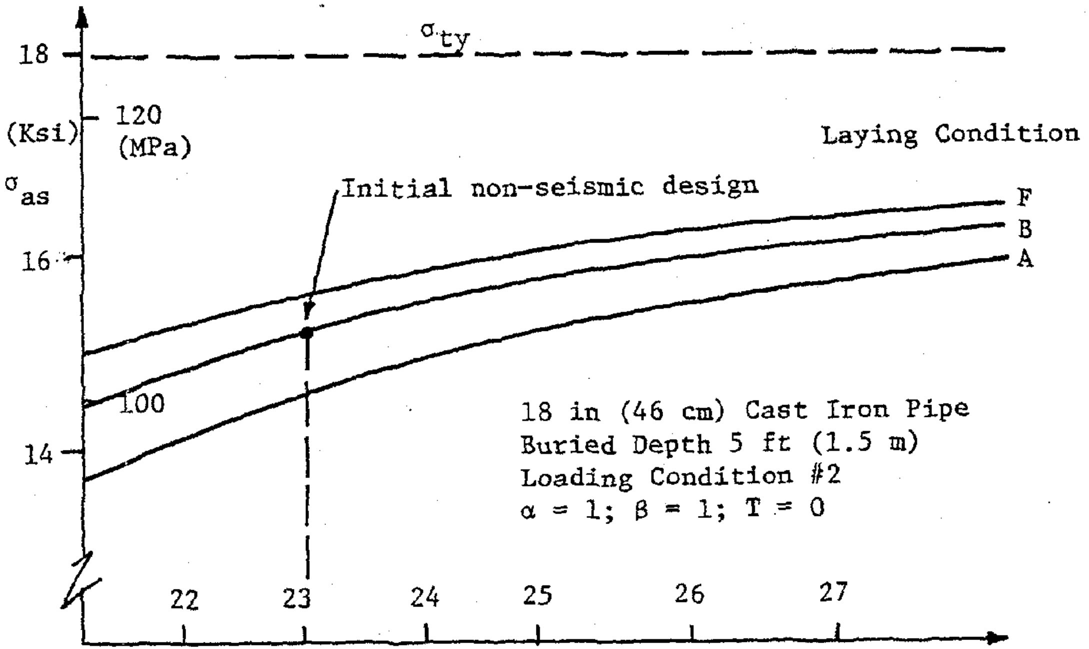

FIG. 5 EFFECT OF LAYING CONDITION ON $\sigma_{as}$

Ductile Iron Pipe (Flexible)

An 18 in (46 cm) diameter ductile iron pipe is also chosen for this parametric study and the analysis is based on the AWWA Specification (2). The pipe data chosen are as follows:

Outside diameter, $d_o$ = 19.5 in. (49.5 cm)
Ultimate tensile strength, $\sigma_{ty}$ = 42 ksi (290 MPa)
Bending strength at yield point, $\sigma_{ty}$ = 72 ksi (495 MPa)
Operating pressure, $p_o$ = 200 psi (1350 KPa)
Surge pressure allowance, $p_s$ = 100 psi (690 KPa)
Depth of cover, h = 5 ft. (1.5 m)
Safety factor, S.F. = 2.0 against internal pressure
1.5 against vertical loads, for bending strength at yield

For ductile iron pipe design, AWWA presents five possible laying conditions shown below. This paper chooses Laying Condition # 2 in its analysis.

| Laying Condition | Description |
|---|---|
| # 1 | Flat-bottom trench: Loose backfill |
| # 2 | Flat-bottom trench: Backfill lightly consolidated to centerline of pipe. |
| # 3 | Pipe bedded in 4-in.-minimum loose soil: Backfill lightly consolidated to top of pipe. |
| # 4 | Pipe bedded in sand, gravel, or crushed stone to depth of 1/8 pipe diameter, 4-in. minimum: Backfill |

compacted to top of pipe. (Approx. 80% Standard Proctor, AASHTO T-99)

#5 Pipe bedded to its centerline in compacted granular material, 4-in. minimum under pipe: Compacted granular or select material to top to pipe. (Approx. 90% Standard Proctor, AASHTO T-99)

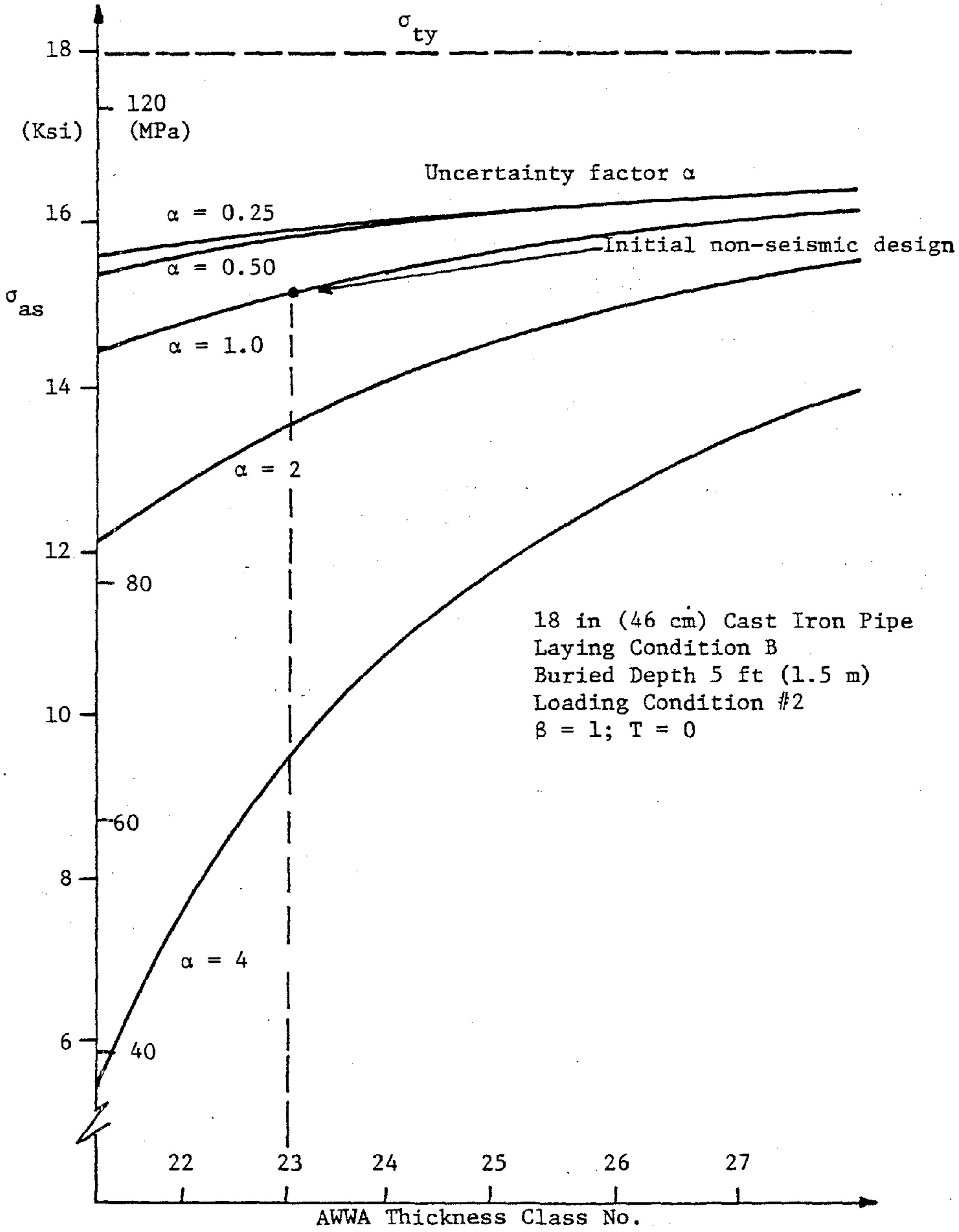

FIG. 6 EFFECT OF UNCERTAINTY TRENCH LOAD FACTOR ON $\sigma_{as}$

As indicated in Fig. 2, the design of ductile iron pipe is controlled by three Loading Conditions shown below:

| Loading Condition | Description |
|---|---|
| 1 | operating water + surge pressures |
| 2 | earth, truck and impact loads |
| 3 | deflection, 3% of diameter |

In this paper, stresses are calculated under all loading conditions and only the critical results are presented.

Following the AWWA code (2), the initial design is controlled by Loading Condition # 1. With the corrosion and manufacturing allowance added, the design thickness between 0.29 in (0.74 cm) and class 50 pipe with a thickness of 0.35 in (0.89 cm) is chosen as the initial design.

As in the cast-iron pipe example, the effects of corrosion (aging), buried depth, laying condition, trench load uncertainty factor and the dynamic water pressures on the reserve axial strengths have been investigated. As an example, Fig. 7 shows the effect of corrosion and thickness class and Fig. 8 shows the effect of buried depth on the reserve axial strength of ductile iron pipes*. For further discussions on the effects of other parameters, readers are referred to the subsequent report (6).

## SUMMARY/CONCLUSIONS

This paper has proposed a "modified" Von Mises failure criterion to evaluate the safety of buried non-homogeneous pipes against earthquakes. Examples of a typical cast-iron pipe and a typical ductile-iron pipe have been presented with the effects of various parameters examined.

In conclusion, the seismic reserve axial strength of buried pipes was found to be influenced by all the parameters investigated. However, the effects from corrosion, loading condition and the trench load uncertainty factor were more pronounced than those from buried depth, laying condition and the dynamic effect on water pressure. It may be concluded that stiffer soil surrounding the buried pipe will result in higher reserve strength.

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* These figures indicate that the *reserve axial strength varies with age* and buried depth.

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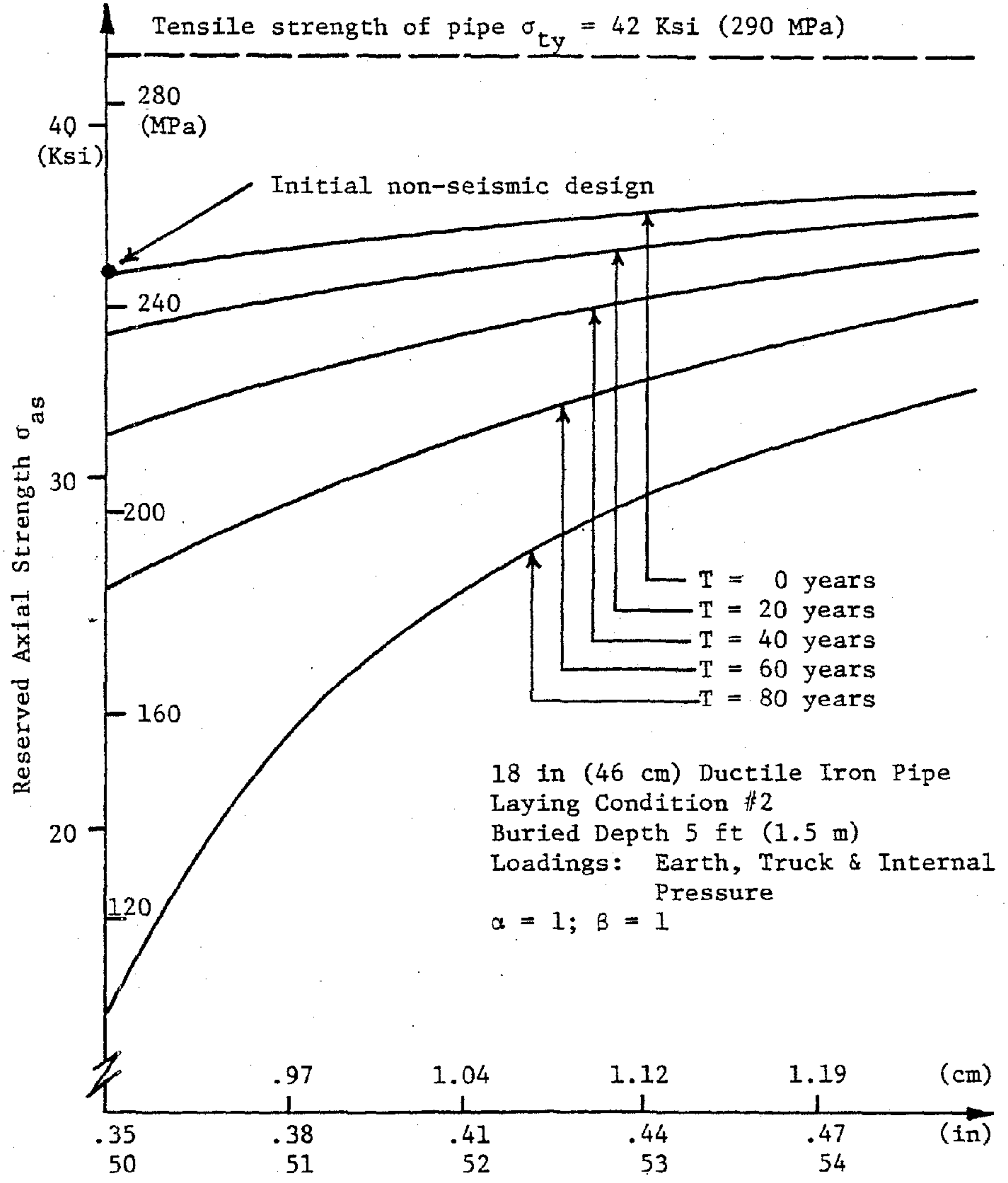

FIG. 7 RESERVED AXIAL STRENGTH VS. THICKNESS

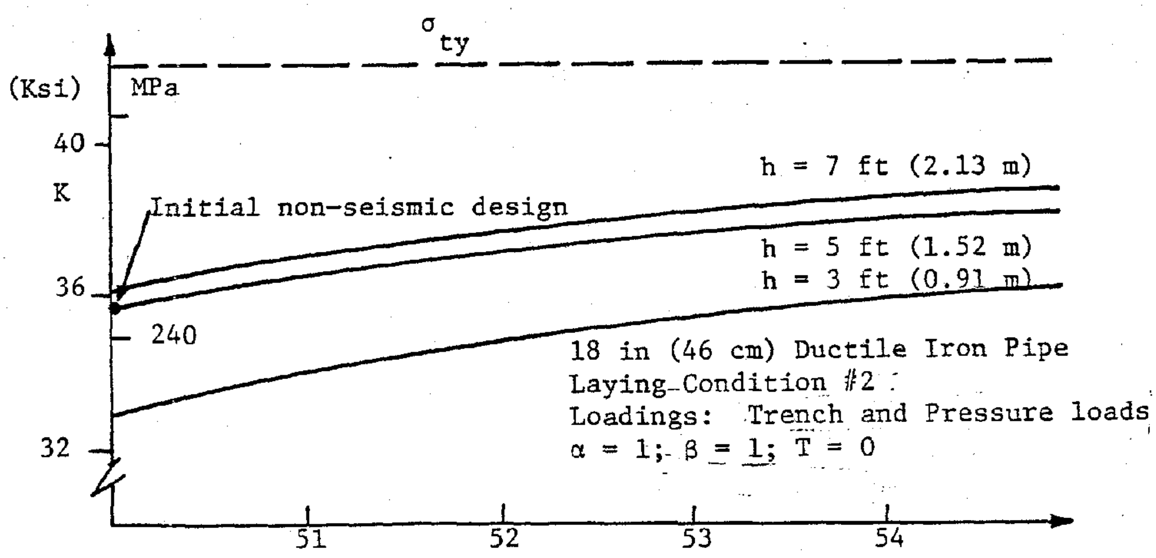

FIG. 8 THE EFFECT OF BURIED DEPTH ON $\sigma_{as}$

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State of the Art of Buried Lifeline Earthquake Engineering
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