# RESPONSE OF BURIED PIPELINES SUBJECT TO EARTHQUAKE EFFECTS

by Michael J. O'Rourke Xuejle Liu



A Regional Corner of Lecritorics in Advanced Individual Apparations

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#### FOREWORD

Earthquakes are potentially devastating natural events which threaten lives, destroy property, and disrupt life-sustaining services and societal functions. In 1986, the National Science Foundation established the National Center for Earthquake Engineering Research to carry out systems integrated research to mitigate earthquake hazards in vulnerable communities and to enhance implementation efforts through technology transfer, outreach, and education. Since that time, our Center has engaged in a wide variety of multidisciplinary studies to develop solutions to the complex array of problems associated with the development of earthquake-resistant communities.

Our series of monographs is a step toward meeting this formidable challenge. Over the past 12 years, we have investigated how buildings and their nonstructural components, lifelines, and highway structures behave and are affected by earthquakes, how damage to these structures impacts society, and how these damages can be mitigated through innovative means. Our researchers have joined together to share their expertise in seismology, geotechnical engineering, structural engineering, risk and reliability, protective systems, and social and economic systems to begin to define and delineate the best methods to mitigate the losses caused by these natural events

Each monograph describes these research efforts in detail. Each is meant to be read by a wide variety of stakeholders, including academicians, engineers, government officials, insurance and financial experts, and others who are involved in developing earthquake loss mitigation measures. They supplement the Center's technical report series by broadening the topics studied.

As we begin our next phase of research as the Multidisciplinary Center for Earthquake Engineering Research, we intend to focus our offorts on applying advanced technologies to quantifying building and lifeline performance through the estimation of expected losses; developing cost-effective, performance-based rehabilitation technologies; and improving response and recovery through strategic planning and crisis management. These subjects are expected to result in a new monograph series in the future.

I would like to take this opportunity to thank the National Science Foundation, the State of New York, the State University of New York at

Buffalo, and our institutional and inclustrial affiliates for their continued support and involvement with the Center I thank all the authors who contributed their time and talents to conducting the research portrayed in the monograph series and for their commitment to furthering our common goals. I would also like to thank the peer reviewers of each monograph for their comments and constructive advice.

It is my hope that this monograph series will serve as an important tool toward making research results more accessible to those who are in a position to implement them, thus furthering our goal to reduce loss of life and protect property from the damage caused by earthquakes

GEORGE C. LEE
DIRECTOR, MULTIDISCIPLINARY CENTER
FOR EARTHQUAKE ENGINEERING RESEARCH

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### PREFACE

#### BY MICHAEL D'ROURKE

Buried pipeline systems are commonly used to transport water, sewage, oil, natural gas and other materials. In the conterminous United States, there are about 77,109 km (47,924 miles) of crude oil pipelines, 85,461 km (53,114 miles) of refined oil proelines and 67,898 km (42,199 miles) of natural gas pipelines (FEMA, 1991). The total length of water and sewage pipelines is not readily available. These pipelines are often referred to as "lifelines" since they carry materials essential to the support of life and maintenance of property. Pipelines can be categorized as either continuous or segmented. Steel pipelines with welded joints are considered to be continuous while segmented pipelines include cast iron pipe with caulked or rubber gasketed joints, ductile iron pipe with rubber gasketed joints, concrete pipe, asbestos cement pipe, etc.

The earthquake safety of buried pipelines has attracted a great deal of attention in recent years. Important characteristics of buried pipelines are that they generally cover large areas and are subject to a variety of geotectonic hazards. Another characteristic of buried pipelines, which distinguishes them from above-ground structures and facilities, is that the relative movement of the pipes with respect to the surrounding soil is generally small and the inertia forces due to the weight of the pipeline and its contents are relatively unimportant. Buried pipelines can be damaged either by permanent movements of ground (i.e. PGD) or by transient seismic wave propagation

Permanent ground movements include surface faulting, lateral spreading due to liquefaction, and landsliding. Although PGD hazards are usually limited to small regions within the pipeline network, their potential for damage is very high since they impose large deformation on pipelines. On the other hand, the wave propagation hazards typically affect the whole pipeline network, but with lower damage rates (i.e., lower pipe breaks and leaks per unit length of pipe). For example, during the 1906 San Francisco earth-

quake, the zones of lateral spreading accounted for only 5% of the built-up area affected by strong ground shaking. However, approximately 52% of all pipeline breaks occurred within one city block of these zones, according to T. O'Rourke et al., (1985). Presumably the remaining 48% of pipeline damage was attributed to wave propagation. Hence, although the total amount of damage due to PGD and wave propagation was roughly equal, the damage rate in the small isolated areas subject to PGD was about 20 times higher than that due to wave propagation.

Continuous pipelines may rupture in tension or buckle in compression. Observed seismic failure for segmented pipelines, particularly large diameters and relatively thick walls, is mainly due to distress at the pipeline joints (axial pull-out in tension, crushing of bell and spigot in compression). For smaller diameter segmented pipes, circumferential flexural failures (round cracks) have also been observed in areas of ground curvature.

This monograph reviews the behavior of buried pipeline components subject to permanent ground deformation and wave propagation hazards, as well as existing methods to quantify the response. To the extent possible and where appropriate, the review focuses on simplified procedures which can be directly used in the seismic analysis and design of buried pipeline components. System behavior of a buried pipeline network is not discussed in any great detail. Where alternate approaches for analysis or design are available, attempts are made to compare the results from the different procedures. Finally, we attempt to benchmark the usefulness and relative accuracy of various approaches through comparison with available case histories.

This monograph is divided into twelve chapters. Chapter 1 reviews seismic hazards and the performance of buried pipelines in past earthquakes. Chapter 2 describes the different forms of permanent ground deformation (surface faulting, lateral spreading, landsliding), and presents procedures to quantify and model both the amount of PGD as well as the spatial extent of the PGD zone. Chapter 3 reviews seismic wave propagation and presents procedures for estimating ground strain and curvature due to travelling wave effects. Chapter 4 presents the failure modes and corresponding failure criteria for buried pipelines subject to seismic effects. Chapter 5 reviews commonly used techniques to model the soilpipe interaction in both the longitudinal and transverse directions.

Chapters 6 and 7 present the response of continuous pipelines subject to longitudinal PGD and transverse PGD respectively, while Chapter 8 discusses pipe response due to faulting. Chapter 9 presents the response of segmented pipelines subject to permanent ground deformation. Chapters 10 and 11 discuss the behavior of continuous and segmented pipeline components subject to seismic wave propagation. Chapter 12 presents current countermeasures to reduce damage to pipelines during earthquakes.

### ACKNOWLEDGMENTS

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Much of the U.S. research reviewed in this monograph was an outgrowth of NCEER projects in the lifeline area. The NCEER Ideline activity was lead by Professor M. Shinozuka, and the authors would like to thank Professor Shinozuka for his tireless leadership of that effort.

The monograph attempts to also include key results from overseas, particularly Japan. Much of the Japanese's research was presented at a series of six U.S. – Japan workshops. This workshop series was originally organized by Professor Shinozuka of the U.S. and the late Professor K. Kubo of Japan. More recently, the workshop series was organized and lead by Professors M. Hamada (Japan) and T. O'Rourke (U.S.). Hence, in addition to their significant individual technical contributions, the authors would like to acknowledge the admirable international cooperation and professional leadership of Professors Hamada, Kubo, T. O'Rourke and Shinozuka

#### ABBREVIATIONS

AC Asbestas Cement

ASCE American Society of Civil Engineers

ATC Applied Technology Council
AWSS Auxiliary Water Supply System

Ct Cast Iron
Conc Concrete Pipe

DI Ductile Iron

EBMUD East Bay Municipal Utility District
ECP Prestressed Embedded Cylinder Pipe

FE Finite Element FS Factor of Safety

I-waves Love Waves

LCP Prestressed Lined Cylinder Pipe LSI Liquefaction Severity Index

MMI Modified Mercalli Intensity

NIBS National Institute of Building Sciences

P-waves Compressional Waves

PE Polyethylene

PGD Permanent Ground Deformation

PVC Polyvinyl Chloride

R-waves Rayleigh Waves

RCC Reinforced Concrete Cylinder Pipe

S-waves Shear Waves

TCLEE Technical Council on Lifeline Earthquake Engineering

WSAW) Welder Steel Arc-Welded Joints
WSC) Welded Steel Caulked Joints
WSGW) Welded Steel Gas-Welded Joints

# NOTATIONS

Λ	cross-section area of pipe	e	pore ratio of soil
a(t)	ground acceleration as a	E	modulus of elasticity
	function of time	E,	initial Young's modulus
a,	critical acceleration	E <sub>p</sub>	modulus of pipe after yield
$A_{core}$	area of the concrete core	€.	sell modulus, $E_i = 2(1+\mu_i)G_i$
$A_m$	maximum ground accel-	F	axial force in pipe
	eration	f	frequency in Hz
a <sub>mus</sub>	maximum acceleration at	Γ,	axial force at the i* joint
_	ground surface	$F_{ei}$	compressive force at joint
a <sub>x</sub>	horizontal acceleration at ground surface	$\vec{\Gamma_i}$	liquefaction intensity factor
a,	vertical acceleration at	$\Gamma_{15}$	average lines contents in
£., <del>,</del>	ground surface		T <sub>15</sub> (%)
C	apparent propagation	F <sub>R</sub>	restraint strength against
	velocity of seismic wave		axial tension
C,,	shear wave velocity of a	g	acceleration due to Earth's
	half space	00	gravity
$C_{i}$	shear wave velocity of	G, G <sub>s</sub>	shear modulus of soil
_	uniform soil layer	-h,Н <sub>х</sub> ,Н <sub>,</sub> -Н	
$\subset_{ph}$	phase velocity of seismic	''	depth to center-line of pipeline
<i>~</i>	wave	$H_{\scriptscriptstyle 1}$	thickness of saturated sand
C,	shear wave velocity of surface soil	' '1	layer (m)
d	closest distance to surface	H,	height of embankment (m)
1.7	projection of fault plane	$H_{i}^{t}$	depth to top of pipe
D	pipe diameter	Ħ,	thickness of uniform soil
$D_{A'}D_{B}$	peak ground displacements	·	layer (m)
$D_{50is}$	mean grain size in T <sub>15</sub> (mm)	l <sub>a</sub>	Arias intensity in gis
d	pull-out capacity of joint	l , 1 k	moment of inertia
	(axial deformation)	k	reduction factor depending
$d_{i}$	lateral deformation		on outer-surface character-
·	capacity of joint		istics and hardness of pipe
$D_{m}$	peak ground displacement	$k_{\sigma}$	coefficient of lateral soil
$D_{N}$	Newmark displacement	v	pressure at rest
	(cm)	Κ,	equivalent soil spring for disturbed soil
$D_{i}$	relative density of soil		20 AM (AGA) arVil

K,	equivalent soil spring for undisturbed soil	M <sub>u</sub>	earthquake magnitude number of joints within
<b>K</b> ,	bearing capacity factor for undrained soil		PGD zone, number of sand layers, or Ramberg
$K_{\mathbf{x}}$	soil stiffness per unit length		Osgood parameter
K,	soil spring constant for movement in horizoidal plane	N <sub>r</sub>	bearing capacity factors for horizontal strip footings for clay
<i>K</i> ,	soil spring constant for downward movement	Nik	horizontal bearing capacity (actor for clay)
К,,	soil spring coefficient for small relative displace-	N <sup>ch</sup>	vertical uplift factor for clay
	ment	$(N_i)_{i \in 0}$	corrected SPT N-value
K	soil spring coefficient for moderate relative dis- placement	N <sub>q</sub>	bearing capacity factors for horizontal strip lootings for sand
$K_{ci}$	soil spring coefficient for relative displacement	$N_{gh}$	horizontal bearing capacity factor for sand
ŧ	equal to or larger than yullength of PGD zone	$N_{qv}$	vertical uplift factor for sand
Ľ	effective shippage length at bend	N,	bearing capacity factors for downward loading for
l,	pipe segment length or		sand
t <sub>a</sub>	distance effective unanchored	þ	internal pressure (operating pressure) in pipe
	length	$p_u$	maximum resistance in
LAR	horizontal projection of inclined rock surface		horizontal transverse direction
Ł,	length of curved portion	Ρ,,	excess pare water pressure
$l_n = -$	critical length of PGD zone	$q_{u}$	maximum resistance in
L,	pipe length in which elastic strain develops		vertical transverse direc- tion
1~	embedment length defined as the length over which	Q	3 <u>Κελ</u> 16 <u>ΛΕ</u> ζ
	the constant slippage force to induce a	R	source distance (km) or pipe radius
	pipe strain $\epsilon$ equal to equivalent ground strain $\alpha$	r	Ramberg Osgood parameter
l <sub>r</sub>	pipe length in which plastic strain develops	r'	parameter of PGD distribu- tion
L,	separation distance	$R_{c}$	radius of curvature of pipe
1.61	between two stations	$r_a$	stress reduction factor
LSI	Liquefaction Severity Index, LSI is arbitrarily truncated at 100	.,	varying from a value of 1 at the ground surface to a value of 0.9 at a depth of
М	bending moment at pipe bent		about 30 ft (10 m)

$R_d$	distance from the epicenter	w	weight of medium
\`d	to site (km)	$rac{\mathcal{W}_{media}}{\mathcal{W}_{\perp}}$	self-weight of pipe
$R_{r}$	Reynolds number (ρVD / η)	$W_{p}$	distance between pipe
$R_{\rm r}$	closest distance to	•	supports
	seismogenic rupture or hypocentral distance	x	non-normalized distance from the margin of the
5	distance between two		PGD zone
-	margins of PGD zone normalized by width W	<b>x</b> ,,	maximum elastic deforma- tion in horizontal axial
5	ground slopes (%) or shear	v	direction
5.	in pipe axial force acted on bent	Y	free face ratio (%)
J,	for Element 1	y	lateral displacement of soil
5 <sub></sub>	normalized distance from	$\mathbf{y}_{t}$	transverse pipe displace- ment in PGD zone
	margin of PGD zone to the location corresponding	$Y_2$	transverse pipe displace- ment outside PGD zone
	to peak transverse ground displacement	Y,,	maximum elastic deforma-
5,,	undrained shear strength of		tion in horizontal transverse direction
D.	surrounding soil	7	maximum elastic deforma-
t	pipe wall thickness	<b>7</b> <sub>0</sub>	tion in vertical transverse
7	shaking period, predomi-		direction
	nant period of soil (s) or	α	inclined angle of slope,
<del>-</del>	axial tension in pipe		adhesion coefficient for
T,5	thickness of saturated cohesionless soils with		clay or equivalent ground
	corrected SPT value less		strain
	than 15 (m)	$\alpha_{\sigma}$	empirical coefficient varying with $S_{\mu}$
t <sub></sub>	maximum resistance in	β	intersection angle between
	horizontal axial direction		pipe and fault trace
$u_f$	joint displacement thresh- old	$\beta_r, \beta_e$	conversion factors
$U_{\mathbf{x}}, u_{\mathbf{x}}$	ground displacement in	$\beta_{eponor}$	optimal orientation of
# "#	longitudinal direction	c	pipeline
$U_{p'} u_{p}$	displacement of pipeline in	β <sub>p</sub>	pipe bunal parameter
p p	longitudinal direction	γ ~	total unit weight critical shear strain
$\nu$	velocity for pipe moving in	$\gamma_{e_i}$	maximum shear strain at
	liquefied soil	$Y_{\alpha}$	pipe-soil interface
V <sub>m</sub>	maximum horizontal	<del>y</del>	effective unit weight of soil
W	ground velocity width of PGD zone	γ,	actual incidence angle of
W,	length from center of PGD	•	S-wave
•	zone to anchor point	δ	permanent displacement of
$W_{\mu c}$	are length of pipe within	\$	ground or pipe critical displacement of
	PGD zone (m)	$oldsymbol{\delta}_{arepsilon}$	ground movement
$W_{\sigma}$	critical width of liquified		p. della moternen
	zone		

δ,	average fault displacement	K <sub>g</sub>	maximum ground curva-
Δ,	pipe displacement at bent		ture
$\Delta L$	total elongation of pipe	λ	wavelength or beam-on-
Δυ	relative displacement at joint		elastic foundation parameter
$\Delta v_z$	deformation capacity of a	ĮL.	friction coefficient
·	joint in compression	Į⊥,	Poisson ratio of soil
$\Delta u_i$	deformation capacity of a joint in tension	ξ	factor which depends on width of PGD, $0.5 \le \xi \le 1$
$\Delta v_{ab}$	relative displacement for	p	density of liquefied soil
	joint closure	σ	uniaxial tensile stress
Δ>,	joint opening due to joint rotation	o,	total overburden pressure on sand layer under
$\Delta x_{i}$ $\Delta x_{i}$	joint opening due to tension		consideration
Δx	total maximum opening at one side of a joint due to transverse PGD	$\sigma'_n$	initial effective overburden pressure on sand layer under consideration
ΔΟ	relative rotation at pipe joint	$\sigma_{\eta}$	axial stress in pipe result- ing from internal pressure
ε	engineering strain	~	compressive strength of
Ē	average pipe strain	$\sigma_{comp}$	concrete
E,	maximum ground strain at $x=U4$	$\sigma_{\alpha}$	ultimate compressive stress of segments
ε,	maximum axial strain due to the elongation of pipe	$\sigma_{p_{t}}$	hoop stress in pipe due to internal pressure
$\mathcal{E}_{t_j}$	pipe bending strain	₹ <b>T</b>	total overburden pressure
$\mathcal{E}_{, pr}$	upper bound for pipe axial strain	$\sigma'_{i}$	effective overburden pressure
$\mathcal{E}_{n}$	ground strain	$\sigma_{i}$	apparent yield stress
$\hat{\epsilon_n}$	pipe axial strain	Ŧ	parameter of PGD distribu-
€,	volumetric strain for		tion
·	saturated sandy soil layer	4 11 T	average shear stress
$\mathcal{E}_{y}$	yield strain	τ,	shear force at pipe-soil
ζ	$\sqrt{K_A/(4FI)}$		interface
η	coefficient of viscosity of liquefied soil	ф	angle of shear resistance of sand
ь,	slope of lower boundary of liquefied layer or ground surface	ф	punciple direction of ground motion