Response of Buried Pipelines Subject to Earthquake Effects

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MCEER
MULTIDISCIPLINARY CENTER FOR EARTHQUAKE ENGINEERING RESEARCH
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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 efforts 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 industrial 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 O'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 pipelines 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 earthquake, 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 soil-pipe 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.

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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 lifeline 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	Asbestos Cement
ASCE	American Society of Civil Engineers
ATC	Applied Technology Council
AWSS	Auxiliary Water Supply System
CI	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
L-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
WSAWJ	Welded Steel Arc-Welded Joints
WSCJ	Welded Steel Caulked Joints
WSGWJ	Welded Steel Gas-Welded Joints

NOTATIONS

A	cross-section area of pipe
$a(t)$	ground acceleration as a function of time
a_c	critical acceleration
A_{core}	area of the concrete core
A_m	maximum ground acceleration
a_{max}	maximum acceleration at ground surface
a_x	horizontal acceleration at ground surface
a_v	vertical acceleration at ground surface
C	apparent propagation velocity of seismic wave
C_H	shear wave velocity of a half space
C_l	shear wave velocity of uniform soil layer
C_{ph}	phase velocity of seismic wave
C_s	shear wave velocity of surface soil
d	closest distance to surface projection of fault plane
D	pipe diameter
D_A, D_B	peak ground displacements
$D_{50_{15}}$	mean grain size in T_{15} (mm)
d_a	pull-out capacity of joint (axial deformation)
d_l	lateral deformation capacity of joint
D_m	peak ground displacement
D_N	Newmark displacement (cm)
D_r	relative density of soil
e	pore ratio of soil
E	modulus of elasticity
E_i	initial Young's modulus
E_p	modulus of pipe after yield
E_s	soil modulus, $E_s = 2(1+\mu_s)G_s$
F	axial force in pipe
f	frequency in Hz
F_i	axial force at the i^{th} joint
F_{cr}	compressive force at joint
F_l	liquefaction intensity factor
F_{15}	average fines contents in T_{15}(%)
F_R	restraint strength against axial tension
g	acceleration due to Earth's gravity
G, G_s	shear modulus of soil
h, H_A, H_B	thickness of layer (m)
H	depth to center-line of pipeline
H_1	thickness of saturated sand layer (m)
H_2	height of embankment (m)
H_c	depth to top of pipe
H_s	thickness of uniform soil layer (m)
I_a	Arias intensity in g's
I_p, I	moment of inertia
k	reduction factor depending on outer-surface characteristics and hardness of pipe
k_o	coefficient of lateral soil pressure at rest
K_1	equivalent soil spring for disturbed soil

K_s	equivalent soil spring for undisturbed soil
K_c	bearing capacity factor for undrained soil
K_g	soil stiffness per unit length
K_h	soil spring constant for movement in horizontal plane
K_v	soil spring constant for downward movement
K_{s1}	soil spring coefficient for small relative displacement
K_{s2}	soil spring coefficient for moderate relative displacement
K_{s3}	soil spring coefficient for relative displacement equal to or larger than y_u
L	length of PGD zone
L'	effective slippage length at bend
L_a	pipe segment length or distance
L_a	effective unanchored length
L_{AB}	horizontal projection of inclined rock surface
L_c	length of curved portion
L_{cr}	critical length of PGD zone
L_e	pipe length in which elastic strain develops
L_{em}	embedment length defined as the length over which the constant slippage force t_u must act to induce a pipe strain ε equal to equivalent ground strain α
L_p	pipe length in which plastic strain develops
L_s	separation distance between two stations
LSI	Liquefaction Severity Index, LSI is arbitrarily truncated at 100
M	bending moment at pipe bent
M_w	earthquake magnitude
n	number of joints within PGD zone, number of sand layers, or Ramberg Osgood parameter
N_c	bearing capacity factors for horizontal strip footings for clay
N_{ch}	horizontal bearing capacity factor for clay
N_{cv}	vertical uplift factor for clay
$(N_1)_{60}$	corrected SPT N-value
N_q	bearing capacity factors for horizontal strip footings for sand
N_{qh}	horizontal bearing capacity factor for sand
N_{qv}	vertical uplift factor for sand
N_γ	bearing capacity factors for downward loading for sand
p	internal pressure (operating pressure) in pipe
p_u	maximum resistance in horizontal transverse direction
P_u	excess pore water pressure
q_u	maximum resistance in vertical transverse direction
Q	$\frac{3}{16}\frac{K_g\lambda}{AE\zeta}$
R	source distance (km) or pipe radius
r	Ramberg Osgood parameter
r'	parameter of PGD distribution
R_c	radius of curvature of pipe
r_d	stress reduction factor varying from a value of 1 at the ground surface to a value of 0 9 at a depth of about 30 ft (10 m)

R_d distance from the epicenter to site (km)

R_e Reynolds number ($\rho VD / \eta$)

R_s closest distance to seismogenic rupture or hypocentral distance

s distance between two margins of PGD zone normalized by width W

S ground slopes (%) or shear in pipe

S_1 axial force acted on bent for Element 1

s_m normalized distance from margin of PGD zone to the location corresponding to peak transverse ground displacement

S_u undrained shear strength of surrounding soil

t pipe wall thickness

T shaking period, predominant period of soil (s) or axial tension in pipe

T_{15} thickness of saturated cohesionless soils with corrected SPT value less than 15 (m)

t_u maximum resistance in horizontal axial direction

u_j joint displacement threshold

U_g, u_g ground displacement in longitudinal direction

U_p, u_p displacement of pipeline in longitudinal direction

V velocity for pipe moving in liquefied soil

V_m maximum horizontal ground velocity

W width of PGD zone

W_a length from center of PGD zone to anchor point

W_{arc} arc length of pipe within PGD zone (m)

W_{cr} critical width of liquified zone

W_{media} weight of medium

W_{pipe} self-weight of pipe

W_s distance between pipe supports

x non-normalized distance from the margin of the PGD zone

x_u maximum elastic deformation in horizontal axial direction

Y free face ratio (%)

y lateral displacement of soil

y_1 transverse pipe displacement in PGD zone

y_2 transverse pipe displacement outside PGD zone

y_u maximum elastic deformation in horizontal transverse direction

z_u maximum elastic deformation in vertical transverse direction

α inclined angle of slope, adhesion coefficient for clay or equivalent ground strain

α_u empirical coefficient varying with S_u

β intersection angle between pipe and fault trace

β_r, β_c conversion factors

$\beta_{optimal}$ optimal orientation of pipeline

β_p pipe burial parameter

γ total unit weight

γ_{cr} critical shear strain

γ_o maximum shear strain at pipe-soil interface

$\bar{\gamma}$ effective unit weight of soil

γ_s actual incidence angle of S-wave

δ permanent displacement of ground or pipe

δ_{cr} critical displacement of ground movement

δ_f	average fault displacement
Δ_l	pipe displacement at bent
ΔL	total elongation of pipe
Δu	relative displacement at joint
Δu_c	deformation capacity of a joint in compression
Δu_t	deformation capacity of a joint in tension
Δu_{ub}	relative displacement for joint closure
Δx_r	joint opening due to joint rotation
Δx_t	joint opening due to tension
Δx	total maximum opening at one side of a joint due to transverse PGD
$\Delta \theta$	relative rotation at pipe joint
ε	engineering strain
$\bar{\varepsilon}$	average pipe strain
ε_{g1}	maximum ground strain at $x=L/4$
ε_a	maximum axial strain due to the elongation of pipe
ε_b	pipe bending strain
ε_{up}	upper bound for pipe axial strain
ε_g	ground strain
ε_p	pipe axial strain
ε_v	volumetric strain for saturated sandy soil layer
ε_y	yield strain
ζ	$\sqrt[4]{K_g/(4EI)}$
η	coefficient of viscosity of liquefied soil
θ_g	slope of lower boundary of liquefied layer or ground surface
κ_g	maximum ground curvature
λ	wavelength or beam-on-elastic foundation parameter
μ	friction coefficient
μ_s	Poisson ratio of soil
ξ	factor which depends on width of PGD, $0.5 \le \xi \le 1$
ρ	density of liquefied soil
σ	uniaxial tensile stress
σ_o	total overburden pressure on sand layer under consideration
σ'_o	initial effective overburden pressure on sand layer under consideration
σ_{ap}	axial stress in pipe resulting from internal pressure
σ_{comp}	compressive strength of concrete
σ_{cr}	ultimate compressive stress of segments
σ_{hp}	hoop stress in pipe due to internal pressure
σ_v	total overburden pressure
σ'_v	effective overburden pressure
σ_y	apparent yield stress
τ	parameter of PGD distribution
τ_{ave}	average shear stress
τ_s	shear force at pipe-soil interface
ϕ	angle of shear resistance of sand
ϕ	principle direction of ground motion