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Soil–structure interaction for deeply buried corrugated steel pipes Part I: Embankment installation

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Abstract

The strengths of buried corrugated steel pipes were studied. There are considerable differences in the fundamental mechanics of earth pressure distribution on rigid pipes and flexible pipes. Corrugated steel pipes are categorized as semi-flexible. The mechanics of soil arching for corrugated steel pipes, therefore, are slightly different from rigid or flexible pipes. Predictor equations for arching factors, deflections, and maximum wall stresses of the corrugated steel pipes were formulated using numerically generated data from soil–structure models. These predictor equations, thus obtained, were compared with currently available equations in order to assess their validity and applicability. A pipe–spring model was used for buckling analyses. The spring coefficients in the pipe–spring model were calculated using the static analyses of soil–structure models. The ultimate and/or critical strengths determined from this study compare well with those from American Iron and Steel Institute (AISI) buckling equations.
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Keywords: Backfill; Buckling; Corrugated steel pipe; Embankment installation; Finite element method; Poisson's ratio; Soil–structure interaction

1. Introduction

Spangler [1] is believed to be the first who studied the behavior of buried metal pipes. As the stiffness of a corrugated steel pipe (referred to as CSP hereinafter) is somewhere between those of rigid concrete pipes and flexible plastic pipes, a corrugated metal pipe may be categorized as semi-flexible [2]. As a consequence, the mechanics of soil arching for CSP are slightly different from rigid or flexible pipes. Although the downward deflection at the top of the CSP, as shown in Fig. 1(a), is small, the relative downward deflection of the adjacent backfill soil prism is greater than that of the central soil prism, thereby inducing a negative arching action. This mechanism is similar to the one occurring in a rigid pipe and results in a vertical arching factor greater than one. In the case of truly flexible pipes, the vertical deflection of the central soil prism is greater than the deflection of the adjacent backfill soil prisms, as shown in Fig. 1(b), and induces a positive arching action resulting in a vertical arching factor less than one. The effects of soil arching are quantified by non-dimensional parameters, vertical and horizontal arching factors, VAF and HAF, respectively. Traditionally, VAF and HAF are calculated using Eqs. (1) and (2) [3].

$$\mathrm{VAF} = \frac{W_e}{\mathrm{PL}} = \frac{2N_{\mathrm{sp}}}{\mathrm{PL}} \tag{1}$$

$$\mathrm{HAF} = \frac{W_h}{\mathrm{PL}} = \frac{N_c + N_i}{\mathrm{PL}} \tag{2}$$

where PL = prism load; W_e = total vertical earth load; W_h = total horizontal earth load; N_{sp} = thrust in the pipe wall at the springline; N_c = thrust in the pipe wall at the crown; and N_i = thrust in the pipe wall at the invert.

This study develops predictor equations for deflections and maximum wall stresses as well as arching factors for CSP using numerical data generated on finite element analyses (referred to as FEA hereinafter). Values from these predictor equations are compared with those computed with currently available equations and close correlations are demonstrated.

Despite a substantial difference in the buckling strengths of CSP determined by the American Iron and Steel Institute (AISI) [4] and AASHTO LRFD [5] procedures, there has been little expressed concern [6]. This is perhaps due to the fact that

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Nomenclature

The following symbols are used in this paper

A_p	area of pipe wall per unit length;
$a_0^*, a_2^*, a_0^{**}, b_2^*, b_2^{**}$	nondimensional parameter;
B	bulk modulus;
B_i	initial bulk modulus;
B_k	nondimensional parameter $= (1 + K_s)/2$;
C_k	nondimensional parameter $= (1 - K_s)/2$;
c	cohesion;
D	pipe diameter;
D_L	deflection lag factor (dimensionless);
E'	modulus of soil reaction;
E_p	modulus of elasticity of steel;
E_t	tangent elastic modulus;
F_{ms}	soil–structure interaction multiplier for maximum wall stress;
F_v	generated friction force or shear stress;
f_{cr}	critical buckling stress ($=f_y$, minimum yield point of steel);
f_u	specified minimum metal strength;
H	backfill height;
H_i	depth of ith soil layer;
HAF	horizontal arching factor;
I	moment of inertia of cross section of the pipe wall per unit length;
K	elastic modulus constant;
K_0	coefficient of lateral earth pressure;
K_B	bedding factor;
K_b	bulk modulus constant;
K_s	lateral stress ratio;
k	soil stiffness factor;
M_S	one-dimensional constrained soil modulus;
m	bulk modulus exponent;
N_c	thrust in the pipe wall at the crown;
N_i	thrust in the pipe wall at the invert;
N_{sp}	thrust in the pipe wall at the springline;
n	elastic modulus exponent;
P_a	atmospheric pressure;
PL	prism load;
q	vertical stress (surface stress) on the crown of pipe;
R	pipe radius;
R_f	failure ratio;
r	radius of gyration;
S_B	bending stiffness parameter;
S_H	hoop stiffness parameter;
UF	extensional flexibility ratio;
VAF	vertical arching factor;
VF	bending flexibility ratio;
W_e	total vertical earth load;
W_h	total horizontal earth load;
α	buckling factor;
γ	unit weight of steel;
γ_i	density of ith soil layer;
Δ_y	vertical decrease in diameter;
μ	frictional coefficient;
ν	Poisson's ratio;
σ_1	maximum principal stress;
σ_3	minimum principal stress;
$\sigma_1^{(i)}$	maximum principal stress in ith layer of soil;
$\sigma_3^{(i)}$	minimum principal stress in ith layer of soil;
σ_m	mean stress;
$\sigma_{\max}$	maximum wall stress;
ε_u	ultimate volumetric strain;
ϕ	angle of internal friction;
ϕ_s	resistance factor for soil stiffness (= 0.9).

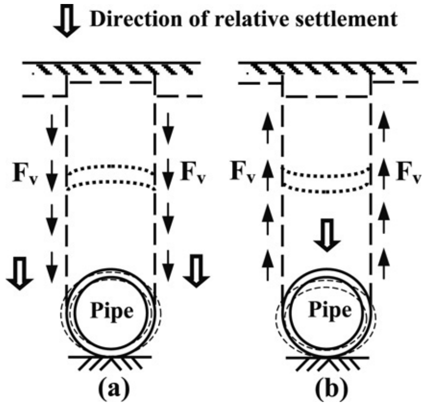

Fig. 1. Pressure transfer within a soil–pipe system: (a) corrugated steel pipe in embankment installation and (b) corrugated PVC pipe in embankment installation (F_v = generated friction forces or shear stresses; interface condition = full-bonded).

there is another limit imposed by the industry with regard to the maximum slenderness ratio (D/r) of CSP permitted. CSP is rarely used with $D/r > 294$, where D = diameter of pipe and r = radius of gyration per unit length. This study formulated a new equation for the buckling strength of CSP based on the soil–structure interaction using FEA and compared results with AISI and AASHTO LRFD procedures.

The primary objective of this study is to evaluate the strengths of CSP so that rational design guidelines can be established. Predictor equations for arching factors, deflections, maximum wall stresses, and buckling strengths are proposed.

2. Background

2.1. Vertical arching factors

Burns and Richard [7] provided theoretical solutions for vertical load on an elastic circular conduit deeply buried in an isotropic, homogeneous infinite elastic medium. According to Burns and Richard, VAF is as follows:

For a full-bonded interface

$$\mathrm{VAF} = 0.714 - 0.714\left(\frac{S_H - 0.7}{S_H + 1.75}\right) + \left(\frac{1.143 + 0.054S_B}{2.571 + 0.572S_H + 0.163S_B + 0.039S_B S_H}\right). \tag{3}$$