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Theoretical and numerical analyses of hydrostatic buckling of a noncircular composite liner with arched invert

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ABSTRACT

This study considered the hydrostatic buckling failure of a noncircular composite liner with an arched invert installed in the sewer pipe. An equation was derived for the buckling of the invert liner, and its application procedure was proposed. A finite-element method was successfully employed for nonlinear and contact analyses of the buckling behaviour and the physical contact phenomena of different sewer culverts. Generally, the composite liner fails in a single-lobe buckling at the invert with the deflection similar to that observed onsite. The proposed theoretical solution was verified through numerical analysis; the critical pressure and buckling mode results showed good agreement.

1. Introduction

Great advances have been achieved in trenchless renewal technologies for pipeline rehabilitation. In particular, modified sliplining (MSL) approaches such as panel lining (PL), spiral wound pipe (SWP), and formed-in-place-pipe (FIPP) have been widely applied to improve the structural and hydraulic performance of a deteriorated trunk sewer through installing a new composite liner inside, as shown in Fig. 1 [1–3]. However, the composite liner needs to be considered its hydrostatic buckling problem because any failure could affect the pipe's structural integrity and drainage function.

Numerous studies in past decades [4–18] investigated the buckling of an encased liner under the external pressure; however, most of them targeted the circular pipe. Thépot [10,11] and Falter [13,14] studied the noncircular liner of a de-bonded (frictionless) liner-pipe systems which are commonly installed by the cured-in-place pipe (CIPP) procedure and are continuities in the cross-sectional geometry (e.g. egg-shaped and semi-elliptical cross-sections). Conversely, there has been little research into liners consisting of two side walls, a crown or apical plate, and an arched invert (e.g. rectangular and horseshoe pipes) (see Fig. 1). The lack of research on the hydrostatic buckling of such a noncircular liner has been identified recently when a buckling failure happened in a renovated rectangular sewer. Fig. 2 shows the buckling deformation observed on-site.

Considering the buckling of the noncircular composite liners with arched inverts is not well understood, the horseshoe-shaped and rectangular liners were selected, and their buckling were studied theoretically and numerically in order to prevent sewer liner from buckling under service conditions. Firstly, a theoretical equation was developed along with the corresponding solution, and a finite element (FE) solution was considered from nonlinear and contact analyses. Next the buckling failure mechanism and behaviour were clarified for different geometries and load conditions,

Abbreviations: R, Radius of the invert liner; t, Thickness of the invert liner wall (equal to the thickness of the plastic liner); L, Perimeter of the invert liner ($=2R\phi_0$); ϕ_0, Half the radial angle of the invert liner; I, Area moment of inertia per unit length of the invert liner ($=t^3/12$); A, Cross-sectional area per unit length of the invert liner ($=t$); A_P, Cross-sectional area of the plastic liner per unit length of the composite liner; A_G, Cross-sectional area of the grout per unit length of the composite liner; E/E_{eq}, Equivalent elastic modulus of the composite liner; ν, Poisson's ratio of the composite liner; E_P, Elastic/Young's modulus of the plastic liner; E_G, Elastic/Young's modulus of the grout; w_0, Maximum deformation of the developed lobe (deformation at the centre of the invert); w, Deformation of the developed lobe; ϕ_{cr}, Half the critical angle of the buckling lobe; q, External water pressure on the composite liner; q_{cr_A}, Theoretical critical pressure of the invert liner; q_{cr_F}, Numerical critical pressure under the full loading condition; q_{cr_P}, Numerical critical pressure under the partial loading condition

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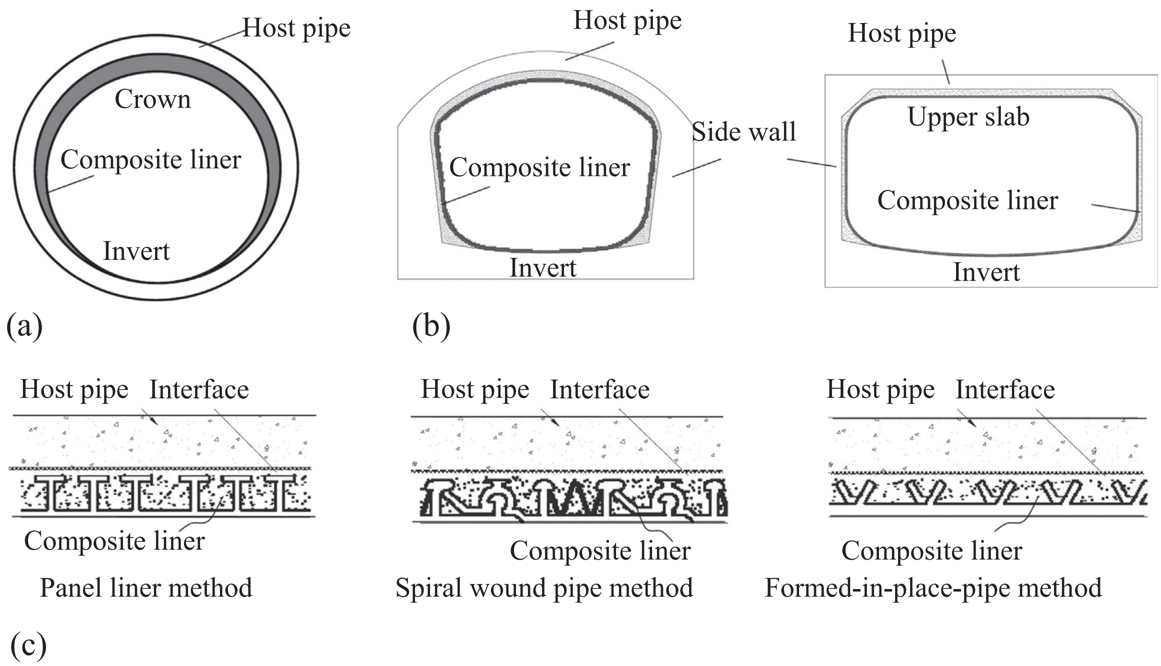

Fig. 1. Renovated trunk sewers: (a) circular pipe, (b) noncircular pipes (horseshoe and rectangular), and (c) cross-section of composite liner due to different sliplining method.

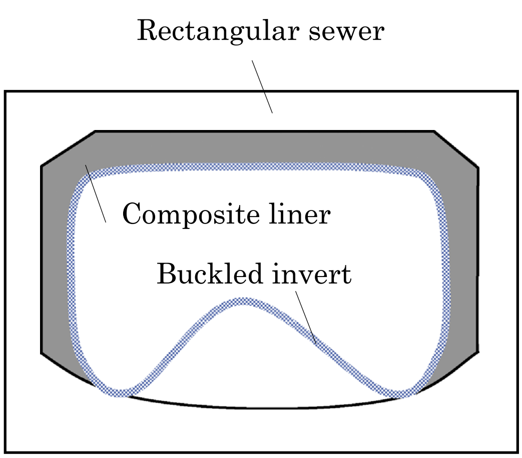

Fig. 2. Local buckling of composite liner installed in rectangular sewer.

and the critical pressure under service conditions was evaluated. Finally, the validation of two solutions was verified through the comparison of the results, e.g. the mode and buckling pressure.

2. Problem definition

The MSL method has been widely used to renovate the aging trunk sewers due to its ability to accommodate arbitrary pipe shapes in Japan [3]. As shown in Fig. 3, the installation is implemented by two main steps: firstly, installing the plastic liner (profile) in the host pipe, and then grouting the annular space to form the new composite liner. In general, grouting uses no-shrink Portland cement-based materials, while the plastic liner depends on the renewal technique: fibreglass panels for the PL method, PVC or PE ribbed profiles for the SWP method, and PVC or HDPE pipe for the FIPP method. However, most of MSL installation inevitably results in a de-bonded liner-to-pipe system because of the lower tensile strength of grout material. In addition, because the plastic liners need to touch the host pipe closely at invert for supporting the entire composite liner and the shape timbering frame during grouting (see Fig. 3(b)), the wall thickness of the composite liner decreases from the upper crown to invert which is eventually considered the same as the plastic liner. Furthermore, the invert liner in sewers is commonly shaped as a downward arc with a larger curvature to meet the hydraulic requirement. Such geometric conditions cause the invert liner buckle more easily when subjected to the hydrostatic pressure; this was actually verified by the recent buckling accident (see Fig. 2). Accordingly, the buckling of the composite liner may be discussed by investigating the invert liner, as shown in Fig. 4(a). The composite liner is considered as an equivalent homogeneous shell with the thickness of the plastic liner and the effective elastic modulus, which can be evaluated based on the equivalence principle of axial rigidity and/or flexural rigidity [19]. The effects of the loading condition on the local buckling of the invert liner may be clarified by applying the hydrostatic pressure acting on overall liner as the full load case and only that acing on invert liner as the partial load case (see Fig. 4(b)).

As a solution to analysis of complex buckling of an encased liner, the finite element (FE) method is always useful [13,18]. However, FE analysis usually takes high costs; therefore, a simpler solution to evaluate the buckling load of the noncircular liner is also required. On the other hand, the existing theoretical solution mentioned above [10,11] unfortunately is unable to apply because they were derived for the egg or elliptical shape noncircular liner composed of several circular arcs with different radii and all members are subjected to the axial compression under hydrostatic pressure. Accordingly, an appropriate theoretical solution should be developed for the studying noncircular liners (see Fig. 1), considering its cross-sectional geometry is consisted of side walls, crown or apical plate, and arched invert and each member behaviours differently under hydrostatic pressure.