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A new method for the structural design of flexible liners for gravity pipes of egg-shaped cross section: Theoretical considerations and formulation of the problem

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ABSTRACT

The majority of gravity pipes with a non-circular cross section have an egg-shaped profile and an inner surface that can be geometrically delineated by three interconnecting circles on each side of a vertical axis of symmetry. Renovation of these pipes can be undertaken at low cost and with minimal surface disruption by installation of a close-fitting polymeric liner, most commonly by the 'cured-in-place pipe' technique.

There are two pre-existing methodologies for the structural design of such liners. Although these procedures have served the international wastewater industry well over an extended period, detailed consideration of both methods suggests that an improved methodology which is straightforward to apply and addresses all relevant issues in a consistent manner would be both technically and financially beneficial. Accordingly a new design method is here proposed, which is based on an assumed displacement distribution in a manner consistent with previous work on close-fitting liners of circular cross section. The new design procedure addresses all the relevant issues in a rational manner, and is readily implemented as a small computer software simulation mountable on any current generation personal computer.

1. Introduction

Pipes with an egg-shaped cross section are commonly encountered in sewerage systems as they offer a good compromise between hydraulic and structural efficiency. Pipes with several other non-circular cross-sectional shapes can also be considered in terms of the same geometrical parameters as the egg [1,2], and therefore analysed in a similar way. In most countries these sewers are typically of brickwork construction, and since the vast majority are now of considerable age many are exhibiting durability problems due to mortar and/or brick loss. If left unchecked this will result in long-term ingress of groundwater and erosion of the soil surround, leading to a gradual loss in shape of the pipe and consequent reduction in safety factor against collapse [2,3].

However, provided the existing system (although deteriorated) is stable, then any appropriate renovation procedure which restores hydraulic integrity of the pipe [3,4] will as a consequence lock the system in its current state, thereby also ensuring long-term structural stability [5,6]. This work is most commonly undertaken by installing a thin-walled close-fitting cured-in-place pipe (CIPP) polymeric liner [3,7–9]. The lining procedure results in a small curing shrinkage gap (separation) between the liner and host pipe; because this is small and discontinuous it tends to be approximately symmetrically distributed around the cross section of the pipe, and the essential components of the lined system from a structural performance point of view are therefore as shown in Fig. 1a. Flexible linings produced using alternative installation techniques can be similarly defined.

Under the conditions described above the liner and host pipe are not bonded, and the only significant load transferred to the liner is the external head of groundwater that must be assumed to build up once pipe hydraulic integrity is restored, and which causes the liner to deform independently within the confines of the essentially rigid host pipe [3,5]. Since a pipe with an egg-shaped cross section has greater height (H) than width (b) (see Fig. 2), application of the external pressure will squeeze the liner so that contact with the host pipe develops from the invert and crown and deflected lobes form [11,12] qualitatively as shown in Fig. 1b. Analogising unit length (i.e. in the direction of the pipe longitudinal axis) of the deflected lobe to an arch under radial pressure loading [10] we surmise that this mode of deformation results in a state of combined flexural and axial stress in the pipe

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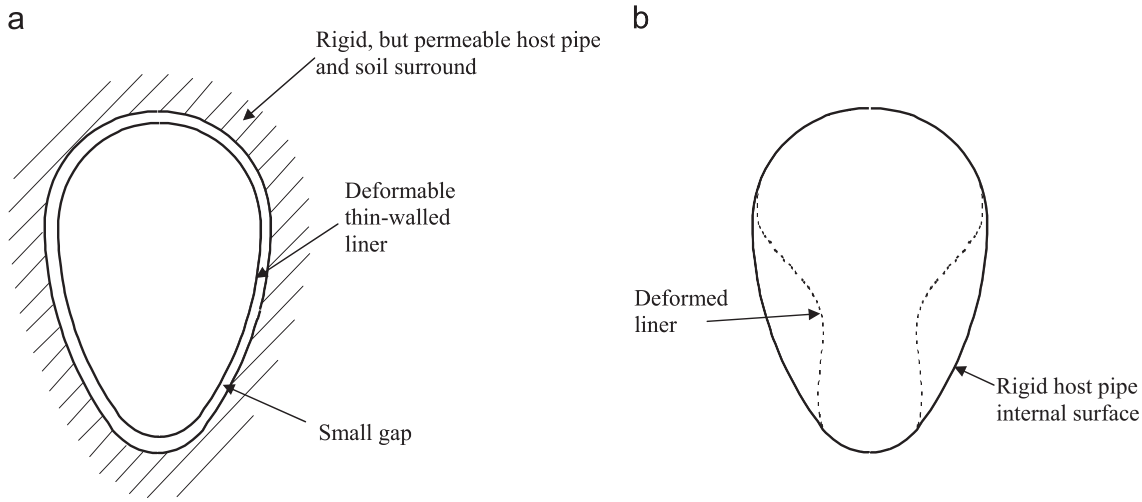

Fig. 1. Basic definition of the structural system under consideration.

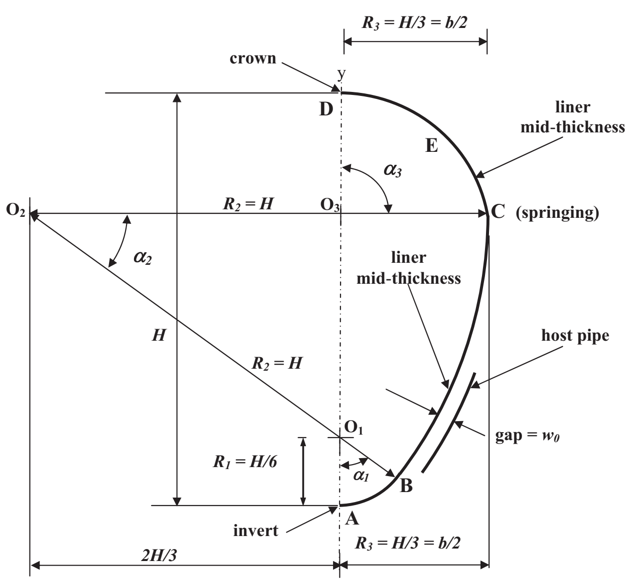

Fig. 2. Basic geometry of a renovated sewer with a standard egg-shaped cross section.

wall, such that liner failure will occur either due to material failure or buckling of the liner wall in the plane of the system cross section. In particular, although commercially installed liners are invariably thin-walled (i.e. thickness«sewer height), since the system initial curvature at the deflected lobe is smaller than that encountered in a circular pipe of equivalent height, failure can no longer be assumed to be caused by buckling [13,14].

The majority of sewers with an egg-shaped cross section, in the UK and many other countries, have a standard '3 × 2' geometry formed from three circular arcs as shown in Fig. 2 with $R_1=H/3$, $R_2=H$, $R_3=H/6$ and centres at O_1, O_2, O_3 respectively. Under these conditions the internal profile of the sewer is perfectly smooth (i.e. without any geometric discontinuities). For the present purposes we assume that any other egg-shaped cross section can be defined with sufficient accuracy as being similarly comprised of three circular arcs with radii R_1, R_2, R_3 defined qualitatively as delineated in Fig. 2. Since the overall structure is symmetrical about the line y–y, attention can be focused on that part of the system to the right of this line. Defining (see Fig. 2) A and D as the invert and crown respectively, with B as the point at which arc_1 and arc_2 are tangential and C as where arc_2 is tangential to arc_3 yields for the standard egg $\alpha_1=53.13°$, $\alpha_2=36.87°$, $\alpha_3=90°$ where α_i is the angle subtended by arc_i at O_i. Thus the standard egg of total internal depth H has a width at the springings (O_3C on Fig. 2) of $2H/3$ and a perfectly smooth perimeter.

Since the liner is taken to be thin-walled, a centroidal model allowing for the arbitrary interaction of flexural and axial compressive effects is appropriate, with liner/host pipe contact occurring at the centroid of the liner [13]. Based on these principles there are two existing design methodologies for these systems, referred to here as the UK and French methods [3,15,16].

2. Consideration of the pre-existing design procedures

The UK design method [3] (also known as the WRc method) was first published in 1983 and has remained unchanged since then; its derivation was presented by Sewerniak and Jones [11]. A finite element mesh of standard linear beam elements was assembled in the shape of a standard egg with dimensions $H=915$ mm (3ft), $b=610$ mm (2ft) supported at 3 points (invert, crown, and a point half way between crown and springings) and subject to an external hydrostatic pressure p. On the assumption that the behaviour of these systems is dominated by bending, a relationship between maximum bending moment (BM) and p was established, whence standard bending theory provides ultimate (strength) and serviceability (deflection) limit states for design purposes.

There are a number of questionable assumptions inherent in this liner design procedure:

- The initial gap, contact conditions, and the associated additional axial compressive stress are not addressed. Fig. 3 shows the relative magnitudes of the bending moment (BM) distribution around the liner perimeter given by the WRc finite element analysis of a standard egg and a corresponding analysis in which outward liner movement is limited by a typical small gap between the liner and the rigid host pipe. It can be seen that there are significant discrepancies throughout the full height of the liner. In particular the WRc analysis gives a maximum value at the invert (where the BM should be zero) rather than close to the mid-span of the deflected lobe as would be expected, and as predicted by the consistent analysis. The WRc analysis (especially the support conditions) was primarily formulated to deal with the problem of a prefabricated liner locally supported and subject to short-term grout