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Role of temporary restraints during installation of sewer linings

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ABSTRACT: The paper summarises some of the results of a numerical parametric study aimed at understanding the structural response of various circular and non-circular (viz. egg-, inverted egg-, elliptical- and horseshoe-shaped) sewer linings. The effects of various restraint conditions, which simulate different temporary support systems that may be used by the contractors during installation of the lining and different loading configurations which may arise at different stages of grouting the annulus gap between the lining and the sewer, have been thoroughly investigated. It has been shown that, by introducing additional temporary restraints before grouting around circular or non-circular sewer linings, considerably higher grouting pressures, leading to a more reliable grouting operation, can usually be attained. A comparison between the various types of restraints on a specific lining has led to enhancement factors for the permissible grouting pressure or, alternatively, to reduction factors in terms of the lining thickness that could be used in designing lining systems. Use of appropriate temporary restraint during installation of sewer linings is expected to lead to a better lining-sewer-soil system.

1 INTRODUCTION

Although preventive maintenance and renovation in one form or another have taken place from the earliest days of sewer construction, it is only relatively recently that sewer rehabilitation has become a subject of increasing interest to the engineering community. Of particular importance is lining the existing sewers of different shapes with glass reinforced plastic, glass reinforced cement, etc., which, besides improving hydraulic characteristics, leads to the enhancement of the structural capacity of the sewer-soil system. Linings also prevents the sewage and waste water from going to the surrounding soil and thereby arrest contamination.

The shape of the lining follows that of the sewer after allowing for an annulus gap so that the sewer lining fits within the existing sewer with a roughly uniform gap between the lining and the sewer walls. Figure 1 shows details of the geometry of the egg-shaped (ES), inverted egg-shaped (IES), horseshoe-shaped (HSS) and semielliptical-shaped (SES) linings that will be studied, in addition to circular linings, under various boundary and installation conditions in this paper. The annulus gap is filled with a cementitious grout which, when set, creates a composite sewer-lining-soil system. Whereas comprehensive design curves pertaining to various criteria may be found in Arnaout, et al. (1988), Pavlovic, et al. (1997) and Seraj, et al. (1997a, 1997b, 1997c), the present paper focuses primarily on the beneficial effect of temporary restraints during installation of linings.

2 GROUTING TECHNOLOGY

2.1 *Method of grouting*

In sewer lining, staged or partial grouting and full grouting are usually adopted. Grout is usually injected through the bottom of the lining. In case of staged grouting, grouting is performed in two stages. The first stage involves grouting the annulus up to the springings, and this is followed by a second stage carried out after the grout of first stage has set. On the other hand, full grouting is performed in a single stage. This technique is more practical than staged grouting.

2.2 *Restraint conditions*

Since the performance of linings of different shapes is particularly sensitive to the type of support provided during grouting, the structural analysis of the sewer linings have been carried out for three different support systems that may be used during installation. These consist of hardwood wedges packed at different locations around the cross-section of the lining on the outside, together with internal struts positioned at the same locations. It is assumed that the packing between the sewer and the lining is closely spaced so that the structure can be studied by means of a two-dimensional finite element model. The three possible support systems considered in the present study are shown in Figure 2 with reference to circular lining.

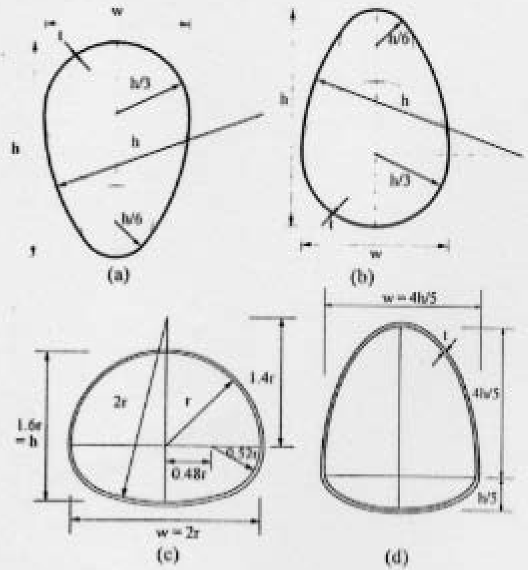

Fig. 1 (a) Egg-, (b) inverted egg-, (c) horseshoe- and (d) semielliptical-shaped sewer linings

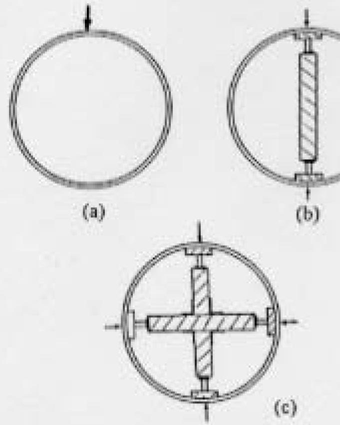

Fig. 2 The support systems studied (with ref. to circular lining): boundary case (a) 1, (b) 2 and (c) 3

2.3 *Load during installation of linings*

Three loading configurations, namely staged grouting pressure, flotation pressure and uniform pressure are adopted throughout the analysis unless otherwise specified. The loading conditions are shown in Figure 3 with reference to HSS lining.

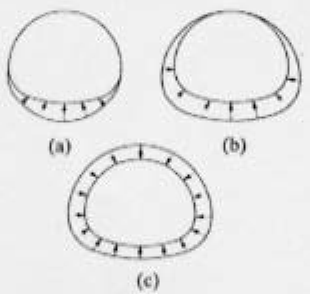

Fig. 3 The loading conditions studied (with reference to horseshoe-shaped lining): (a) staged grouting, (b) pressure up to crown only and (c) uniform pressure

2.4 *Basis of design*

All properly designed sewer linings must satisfy both stress-, deflection-limit and, if applicable, buckling criteria. Here, the stress-limit criteria is so defined that the maximum bending stress developed during grouting must not exceed the allowable bending stress of the lining material. For deflection-limit criteria, a maximum allowable deflection in the lining not exceeding 3 percent of the width of the lining, as advocated by the Water Research Centre (1983), has been adopted for all the linings.

3 ANALYSIS TECHNIQUE

3.1 *Parameters used*

Geometrical parameters include width, height and thickness of lining (w, h and t). Material parameters include allowable short-term bending stress (S_s), short-term modulus of elasticity (E_s) and Poisson's ratio (ν) of lining. Load parameters include unit weight of grout mix (G) and excess head of grout measured from crown of lining conforming to uniform pressure load (H).

3.2 *Equations involved*

The dimensionless equations corresponding to the bending stress S and the deflection δ at any point on the lining can be written for the three load cases as follows:

(a) Staged Grouting (Figure 3a)

$$S / Gw = A(w / t)^2 \quad (1)$$

$$\delta / w = (B_x^2 + B_y^2)^{1/2} K \quad (2)$$

(b) Flotation (Figure 3b)

$$S / Gw = C(w / t)^2 \quad (3)$$

$$\delta / w = (D_x^2 + D_y^2)^{1/2} K \quad (4)$$

(c) Uniform Pressure (excess head H) (Figure 3c)

$$S / Gw = E(H / w)(w / t)^2 \quad (5)$$

$$\delta / w = (F_x^2 + F_y^2)^{1/2} (H / w) K \quad (6)$$

where $K = (Gw / E_s)(w / t)^3$ (7)

In these equations, S/Gw can be regarded as a non-dimensional stress while δ/w is the deflection related to the size of the lining and K is a measure of lining flexibility. Here, A, C, E, B_x, B_y, D_x, D_y, F_x and F_y are all constants which depend on the boundary set-up adopted during the grouting of the annulus and loading configurations used in the analysis.

The total bending stress S_t and the total deflection δ_t at any point in a lining subjected to a head of grout which is greater than the lining height h (i.e. full flotation) can be divided into values of bending stress and deflection resulting from the two loading cases of pressure up to the crown (i.e. flotation) and uniform pressure. This implies that, by adding Equations 3 and 5, and Equations 4 and 6, the following dimensionless equations for the total bending stress and the total deflection can be found.

$$S_t / Gw = \left|(C + E(H / w))(w / t)^2\right| \quad (8)$$

$$\delta_t / w = (M_x^2 + M_y^2)^{1/2} K \quad (9)$$

where,

$$M_x = D_x + F_x(H / w) \quad (10a)$$

$$M_y = D_y + F_y(H / w) \quad (10b)$$

Since the maximum bending stress and the maximum defection in a lining must not exceed the respective values of S_s and $0.03\ w$, the values of S_t and δ_t in Equations 8 and 9 can be replaced by S_s and $0.03w$, respectively. As the point of injection of the grout is usually located at the invert of the lining, it is convenient to replace the value of H in Equations 8 and 9 by the equivalent expression $(p/G) - h$, where p is measured from the invert of the lining. As a result, Equations 8 and 9 can be rewritten to produce the following design equations.

$$R = \left|C + E(p / Gw - h / w)\right| \quad (11)$$

where,

$$R = (S_s / Gw)(t / w)^2 \quad (12)$$

and

$$0.03 / K = (N_x^2 + N_y^2)^{1/2} \quad (13)$$

where,

$$N_x = D_x + F_x(p / Gw - h / w) \quad (14a)$$

$$N_y = D_y + F_y(p / Gw - h / w) \quad (14b)$$

In cases where buckling is to be considered, dimensionless Equations 15 and 16 apply for flotation and uniform pressure cases, respectively (Pavlovic, et al. 1995). Here, M corresponds to the membrane stress at any point in the lining.

$$M / Gw = \alpha(w / t) \quad (15)$$

$$M / Gw = \beta(w / t)(H / w) \quad (16)$$

This leads to the following dimensionless equation for the total membrane stress (M_m) at any point in the lining under full grouting:

$$(M_m / Gw)(t / w) = (\alpha + \beta(H / w)) \quad (17)$$

Equating M_m with the critical buckling stress of a hinged arch of equivalent radius and unrestrained length (Timoshenko and Gere 1961), as reported by Pavlovic, et al. (1995) for circular lining, the stiffness of lining (S_F) is approximately given by the following dimensionless equation:

$$(S_F / Gw) = (1/4Q)(\alpha - \beta + \beta(p / Gw)) \quad (18)$$

where, $S_F = (1/12)(E_s / (1 - \nu^2))(t / w)^3$ and Q is equal to 3 for boundary condition 2 and 15 for boundary condition 3.

For any particular lining geometry and material properties, the above equations must be satisfied at the locations of maximum bending stress, deflection and axial stress in the lining. The maximum allowable grouting pressure p which can be applied on the lining during grouting is the minimum of the p values as determined by all the criteria.

3.3 *Numerical simulation*

A linear two-dimensional finite-element (FE) model is used in order to simulate the behaviour of sewer linings of different shapes under various probable loads during installation. The thickness of the lining is assumed to be constant all around the cross-section. Due to symmetry of the lining geometry, loading and boundary conditions about the vertical axis, only half of the cross-section is analysed. The elements used in the analysis are two-noded beam elements each having three degrees of freedom (horizontal and vertical displacement, and rotation) at each node.

The restraints due to the support system shown in Figure 2 are simulated numerically in the analysis by fixing the horizontal and vertical components of displacement at the corresponding nodal points. This involves a small approximation in that the deformation in the restraining struts is ignored, the strut being very stiff compared with the lining.

The various loading configurations shown in Figure 3 have been simulated by applying equivalent point loads at appropriate nodes. A typical two-dimensional finite element mesh, adopted in the analysis of inverted-egg shaped sewer linings, is given in Figure 4. Mesh for other linings are similar.

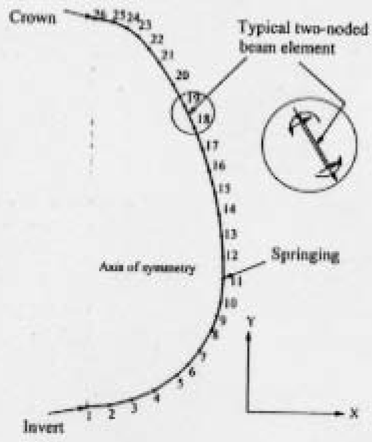

Fig. 4 IES lining: Two-dimensional finite element mesh adopted in the analysis

3.4 *Design curves*

For each load and boundary case, the parametric analysis is carried out by varying one parameter at a time. The results (bending stresses, deflections and axial stresses) are given in terms of dimensionless equations linking all the independent parameters together. The non-dimensional bending stress *(S/Gw)* and deflection *(δ/w)* are plotted against $(w/t)^2$ and lining flexibility *K*, respectively for staged grouting and flotation load, and against $(H/w)(w/t)^2$ and $(H/w)K$ for uniform pressure. Similarly, the non-dimensional membrane stress *(M/Gw)* is plotted against *(w/t)* and *(w/t)(H/w)*, respectively for flotation and uniform pressure cases. From these plots, constants for the maximum bending stress, maximum deflection and maximum membrane stress in the lining are computed for different boundary cases and different loading configurations. The value of these constants are employed in getting relationship of *p* with *R*, *K* and *M*. Once a boundary case is selected and the geometric and material parameters are chosen, a value of allowable grouting pressure based on the stress-limit, deflection-limit and, if applicable, buckling-criteria can be determined using appropriate curves. For circular linings, buckling criterion alone has been considered as membrane stress dominates in such linings. While comprehensive design curves pertaining to various criteria may be found in Arnaout, et al. (1988), Pavlovic, et al. (1997) and Seraj, et al. (1997a, 1997b, 1997c), Figures 5 and 6 give design curves for inverted-egg shaped sewer linings for different boundary conditions, based on stress- and deflection-limit criteria. The least of the two grouting pressures

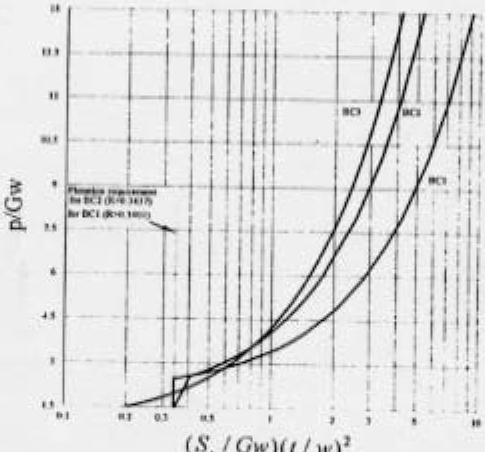

Fig. 5 IES lining: Allowable grouting pressure for different boundary conditions, based on stress-limit criteria

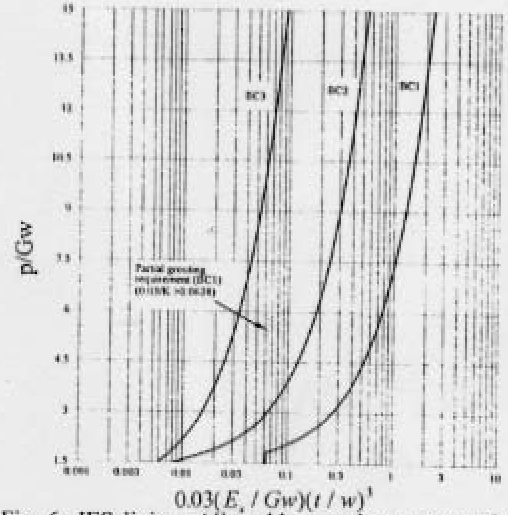

Fig. 6 IES lining: Allowable grouting pressure for various boundary cases, based on deflection-limit criteria

is the allowable grouting pressure for this particular lining. It is clear that as the amount of restraints increases, the allowable grouting pressure increases.

3.5 *Enhancement factors*

Both the maximum bending stress and the maximum deflection in a lining that arise from grouting pressure can be reduced by introducing additional restraints during installation. Similarly, additional restraints also result in an increase in resistance against buckling of the lining. This implies that an enhancement in the value of the grouting pressure can be achieved, thus ensuring adequate grouting of the annulus. This gives rise to the introduction of what can be termed an enhancement factor (EF). Here, for stress-limit and deflection-limit criteria, the enhancement factor is defined as the ratio of the allowable grouting pressure which could be applied on any particular lining using boundary case 2 or 3 to the one corresponding to boundary case 1, i.e.

$$EF_i = p_i / p_1 \tag{19}$$

Here i corresponds to boundary cases 2 or 3. Since, in the present study, only boundary cases 2 and 3 have been considered in the buckling analysis, the corresponding enhancement factor for this third criterion is given by p_3/p_2.

Values of EF are determined for each of the stress limit, deflection-limit and, if applicable, buckling criteria. It has been observed that the EFs for deflection-limit criteria are much higher than their stress-limit and buckling counterparts, and, thus, *will not govern* the design.

Enhancement factors has been calculated for boundary conditions 2 and 3. Such factors for horseshoe-shaped linings based on stress-limit and buckling criteria are plotted in Figure 7. Similar curves for other linings types may also be found.

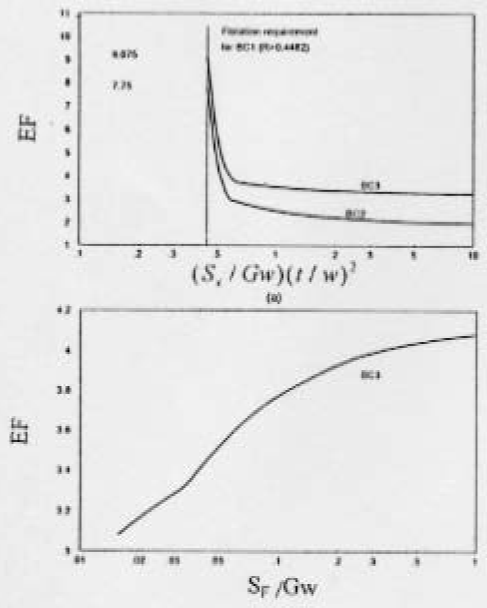

Fig. 7 HSS lining: Enhancement factors for allowable grouting pressure based on (a) stress-limit criteria and (b) buckling criteria

From the figure, it can be deduced that the highest possible enhancement in the allowable grouting pressure, for stress-limit criteria, that can be achieved for adopting boundary conditions 2 and 3, instead of boundary condition 1, are 7.75 and 9.075, respectively. As the value of R increases gradually from 0.4482 to 0.5820, the value of enhancement factor sharply decreases from 7.75 to 2.99 for boundary case 2 and from 9.075 to 3.770 for boundary case 3. Beyond this range of R, the EF gradually decreases, attaining virtually constant values for both boundary conditions. The enhancement factors corresponding to the buckling criterion are also above 3, for using boundary condition 3 instead of 2 during installation of HSS linings. Similar enhancements have also been found for other linings.

3.6 *Reduction factors*

Once a value of allowable grouting pressure is determined for any particular lining using a certain restraint set-up, a considerable reduction in the allowable thickness of the lining can usually be achieved if additional restraints are used instead. This gives rise to the introduction of another factor, called the reduction factor (RF), which is defined below.

For stress-limit criteria, the reduction factor is defined as the ratio of the lining thickness resulting from the use of boundary case 2 or 3 to the one corresponding to boundary case 1. The equation used to calculate the values of RF is as follows:

$$RF_i = t_i / t_1 \tag{20a}$$

where

$$t_i = [C_i + (p / Gw - 0.8)E_i]^{1/2} \, [Gw^3 / S_a]^{1/2} \tag{20b}$$

and

$$t_1 = [C_1 + (p / Gw - 0.8)E_1]^{1/2} \, [Gw^3 / S_a]^{1/2} \tag{20c}$$

with i corresponding to boundary cases 2 or 3, and other variables being defined earlier.

The reduction factors corresponding to buckling criteria are given by the ratio t_3/t_2 since, as for the enhancement factors considered earlier, only boundary cases 2 and 3 are considered. Here, the RF is found as follows:

$$RF_3 = t_3/t_2 \tag{21}$$

The reduction factors for semielliptical-shaped linings based on stress-limit and buckling criteria are plotted in Figure 8. Once again, similar curves for other linings types were also studied. It can be seen from Figure 8(a) that considerably larger reduction factors are achieved, under stress-limit criteria, by using boundary case 3 when compared with boundary case 2. Again, the figure shows that, for boundary case 2, a minimum value of p_1/Gw equal to 6.7 is needed in order to achieve reduction factors less than one. Thus no beneficial effect can result from the use of boundary case 2 if the value of p_1 is less than 6.7 *Gw*.

The reduction factors based on the buckling criterion, as shown in Figure 8(b), reveals that, whereas under boundary condition 2, either stress or buckling criteria may govern the determination of reduction factors, under boundary condition 3, stress-limit criteria will invariably turn out to be the most critical consideration.

Again, stress and buckling limitations proved to be more critical for the determination of RFs, and, hence reduction factors under deflection-limit criteria are not reported here. Similar conclusions are valid for other linings, as well.

It has been found that restraints in circular linings do not reduce appreciably the membrane stresses. A recent study (Pavlovic, et al. 1997) has reported some test results showing that the restraint systems provided only a minor contribution to the reduction of stresses/strains in the lining since, as a result of these restraints, the values of membrane strains and displacements were usually only slightly reduced. Nevertheless, additional restraints lead to a stiffer structure with higher critical buckling pressures.

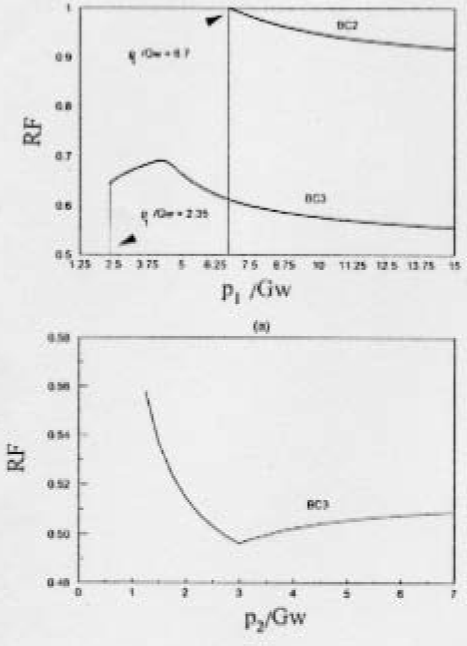

Fig. 8 SES lining: Reduction factors for minimum permissible lining thickness based on (a) stress-limit criteria, and (b) buckling criteria

4 CONCLUSIONS

It has been shown that, by introducing additional temporary restraints before grouting around sewer linings, usually considerably higher grouting pressures, leading to a more reliable grouting operation, can be attained. In the study, it has been assumed that all restraints are fully effective, so that the restrained points of the lining are prevented from moving in any direction. Such ideal conditions will very nearly be realised if internal supports coupled with external packing are effectively provided.

In the case of the approximate buckling analysis, introduction of additional restraints reduced the effective length of the arch between the restraints, thus leading to a stiffer structure with higher critical buckling pressure. The presently considered buckling criterion assumes an uniform pressure intensity on the arch; such a criterion may easily be achieved if linings of adequate thickness and acceptable physical properties are employed in design.

In general, boundary case 3 having both horizontal and vertical restraints has been found to lead to most satisfactory grouting operation leading to most efficient lining-sewer-soil system

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