Grouting and Deep Mixing, Yonekura, Terashi & Shibazaki (eds) © 1996 Balkema, Rotterdam. ISBN 90 5410 805 3

Allowable grouting pressure during installation of non-circular sewer linings

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ABSTRACT: The lining of newly-built or existing sewers of different shapes, apart from improving hydraulic characteristics, leads to the enhancement of the structural capacity of the sewer-soil system. Linings also prevent the sewage and waste water from going to the surrounding soil and thereby arrest contamination. The annulus gap between the sewer and similarly shaped lining is usually filled with a cementitious grout under pressure during the installation of the lining. The allowable grouting pressure that can be applied to the lining is dictated by the stress-limit criterion, deflection-limit criterion and, in some cases, buckling-limit of the lining. The present paper presents comprehensive design curves for the determination of allowable grouting pressure during installation of linings of various non-circular sewers having arbitrary material properties and capacities under various installation conditions. These curves, apart from help designing various sewer linings, are instrumental in determining the efficiency of a particular lining geometry.

1 INTRODUCTION

Sewer linings are usually made of glass-reinforced plastic (GRP) or glass-reinforced cement (GRC). Steel linings are also used. 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 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 structure. Grouting pressure plays an important role in this respect. Grout under higher pressure usually ensures proper filling of the annulus gap. However, higher pressure results in the necessity of increase in the lining thickness. The allowable grouting pressure is generally governed by stress-limit and deflection-limit criteria for ES and IES linings. For HSS and SES linings, buckling criteria is also to be considered.

2 TECHNIQUES 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. However, during full grouting, the lining is subjected to higher pressure so that a thicker lining or additional supports may be deemed essential in an effort to avoid excessive deformation or overstressing.

3 RESTRAINT SET-UPS

The performance of linings of different shapes is particularly sensitive to the type of support provided during grouting. Because of this, 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 (typically, not exceeding 1-1.5 m spacing), 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 HSS lining. Boundary condition

1 consists solely of a restraint at the crown (top) of the lining. The second support system comprises restraints at both the crown and the invert of the lining. This boundary condition is vertically stiffer than the former. The supports of boundary condition 3 consist of restraints at the crown, invert and springing (or any other points) of the linings. In case of ES and IES linings, the horizontal support, under boundary case 3, was placed at the springings (along the diameter of the circle having radius h/3 - see Figures 1a, 1b), whereas in case of SES lining the horizontal support was placed at one-third height from the bottom.

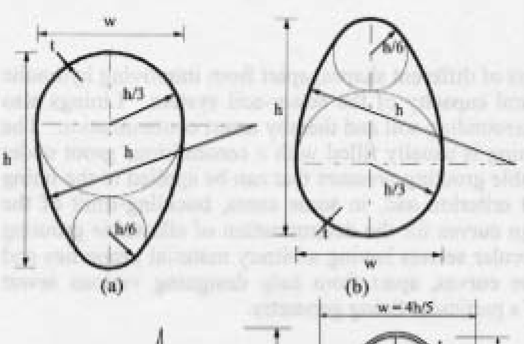

Fig. 1 (a) Egg-, (b) inverted egg-, (c) horseshoe- and (d) semielliptical-shaped sewer linings

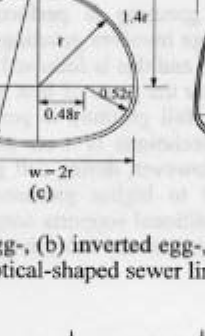

Fig. 2 The support systems studied (with reference to horseshoe-shaped lining): (a) boundary case 1, (b) boundary case 2 and (c) boundary case 3

4 LOADING CONFIGURATIONS

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 IES lining.

Staged-grouting corresponds to pressure from grout surrounding the lining up to the height of the springings (or one-third height from bottom for SES lining), as shown in Figure 3a, and so simulates the first phase of staged grouting.

Flotation pressure involves a head of grout up to the crown, as in Figure 3b. In this situation, the lining is just covered by grout and hence the buoyancy force acting on the lining is the maximum that can occur.

The third load configuration, shown in Figure 3c, corresponds to the uniform pressure which is applied on the lining as a consequence of an excess head of grout. Flotation pressure and uniform pressure can be superimposed in order to simulate any grout pressure applied on the lining during full grouting.

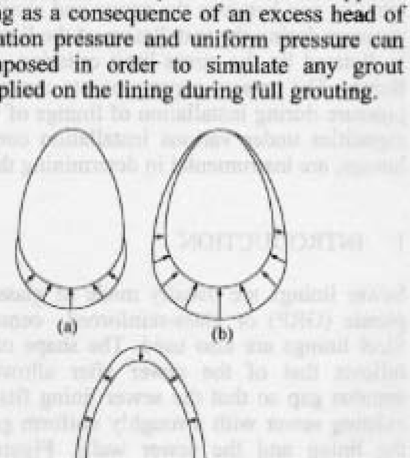

Fig. 3 The loading conditions studied (with reference to inverted egg-shaped lining): (a) staged grouting, (b) pressure up to crown only and (c) uniform pressure

5 CALCULATION OF LOADS

For each load configuration and boundary case, the parametric study is carried out by varying one parameter at a time, keeping the others constant. The results are most conveniently given in terms of dimensionless equations linking all the independent parameters together. Such equations are derived on the basis of a curve-fitting exercise. In considering this, it should be noted that, in the case of the loading corresponding to flotation and the first phase of staged grouting, the applied load is defined by the lining height h and the specific weight of grout mix G. In these two loading cases, the applied pressure at any point on the lining can be calculated by multiplying the specific weight of the grout mix by the distance from the top of the grouting to the point at which the pressure is calculated. For the uniform load case, on the other hand, the external load is defined by the values of excess head of grout H (and its specific weight G) and is independent of the height of the lining.

6 BASIS OF DESIGN

All properly designed sewer linings must satisfy both stress- and deflection-limit criteria. In case of HSS and SES linings, large amount of membrane stress develops during grouting and their design have been checked against possible failure due to buckling, as well. 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 non-circular linings.

7 PARAMETERS USED IN THE ANALYSIS

The parameters included in the subsequent analysis are divided into geometrical, material, and load parameters.

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).

8 MATHEMATICAL FORMULATION

It is advantageous and convenient to express the results of the analysis in terms of nondimensional equations encompassing all the parameters involved in the analysis. Thus the design curves that will be proposed after an extensive parametric analysis of variedly shaped sewer linings can be used for all types of lining materials and lining sizes of that specific shape. 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.

9 FINITE-ELEMENT MODEL

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.

10 DESIGN CURVES

The areas of sewer linings of different shapes as shown in Figure 1 have been plotted against h in Figure 4. The use of these curves will be shown in the next section.

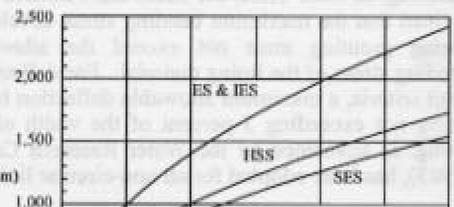

Fig. 4 Relationship between area and height of various non-circular sewers

For each load and boundary case, the parametric analysis is carried out by varying one parameter at a time, keeping the others unchanged. The results (bending stresses, deflections and axial stresses) are given in terms of dimensionless equations linking all the independent parameters together as described earlier. 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 criteria can be determined using Figures 5, 6 and 7. Figures 8, 9 and 10 summarise the results of all the three boundary cases based on deflection-limit criteria and hence can be used to determine the allowable grouting pressure in any particular lining. Similarly, Figure 11 caters for the determination of allowable grouting pressure when membrane stresses are prominent. In Figure 11, boundary condition 1 is not included since the methodology adopted in the present study can not account for this; the design of HSS and SES linings also become uneconomical when, in fact, boundary condition 1 is employed during the installation of these linings. A more elaborate - and sometimes more rational - account of the formulation of design curves may be found in Arnaout, et al. (1988) and Seraj, et al. (1995a, 1995b, 1995c).

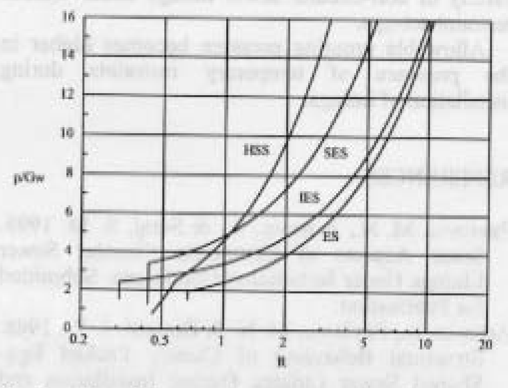

Fig. 5 Allowable grouting pressure based on stress limit criterion (boundary condition 1)

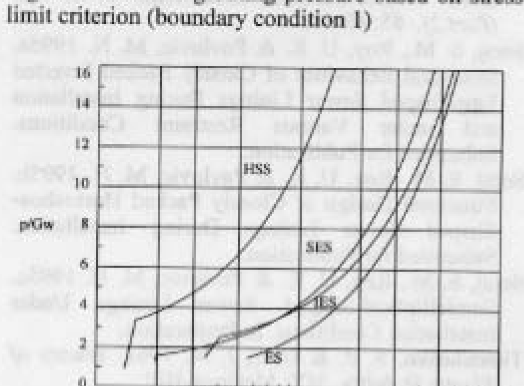

Fig. 6 Allowable grouting pressure based on stress limit criterion (boundary condition 2)

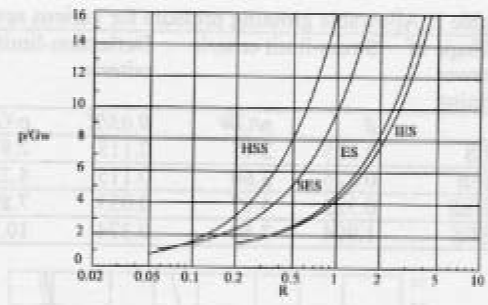

Fig. 7 Allowable grouting pressure based on stress limit criterion (boundary condition 3)

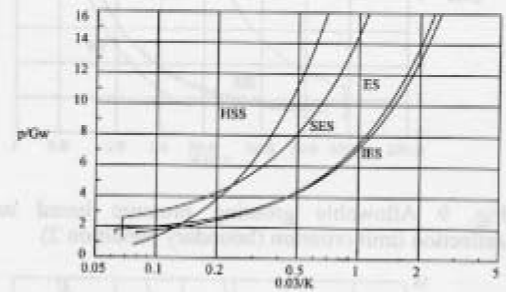

Fig. 8 Allowable grouting pressure based on deflection limit criterion (boundary condition 1)

11 DESIGN EXAMPLE

Data to be used to illustrate the use of the curves presented:

Lining material = GRP
$E_s = 20 \times 10^6$ kN/m^2; $S_s = 60 \times 10^3$ kN/m^2; G = 16.5 kN/m^2; t = 12 mm; $\nu = 0.23$; annulus grouting spacing = 25 mm.
Let the cross-sectional area of the sewer be 1.0 m^2. From Fig. 4, the h and w of sewers of different shapes are calculated and given below in Table 1:

Table 1. Determination of h and w for sewer.

Shape	h, mm	w, mm	effective w, mm
ES	1400	933	859
IES	1400	933	859
HSS	1000	1250	1176
SES	893	714	640

Assuming that boundary condition 2 will be adopted during the installation of linings, Figures 6, 9 and 11 are used to determinate the allowable grouting pressure for linings of different shaped sewers having 1.0 m^2 area (see Table 2).

Table 2. Allowable grouting pressure for various sewers having cross-sectional area equal to 1.0 m^2.

Shape of sewer lining	Stress-limit criteria		Deflection-limit criteria		Buckling criteria		Allowable grouting pressure	
	R	p/GW	$0.03/K$	p/Gw	$4QS_F/GW$	p/GW	p/GW	p (kN/sq. m)
ES	0.825	2.15	0.115	2.87	N/A	N/A	2.15	30.5
IES	0.825	3.60	0.115	4.22	N/A	N/A	3.60	51.0
HSS	0.322	4.97	0.033	7.89	1.156	3.10	3.10	60.2
SES	1.994	7.50	0.374	10.92	13.181	18.60	7.50	79.2

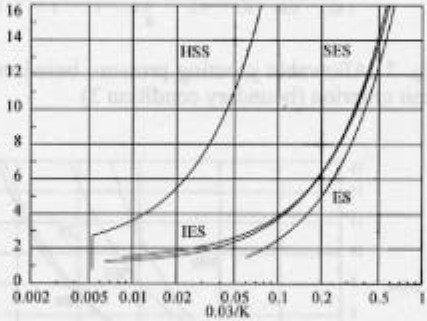

Fig. 9 Allowable grouting pressure based on deflection limit criterion (boundary condition 2)

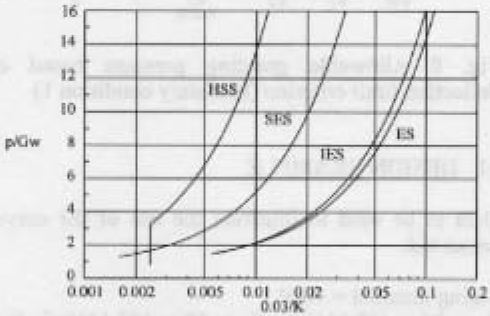

Fig. 10 Allowable grouting pressure based on deflection limit criterion (boundary condition 3)

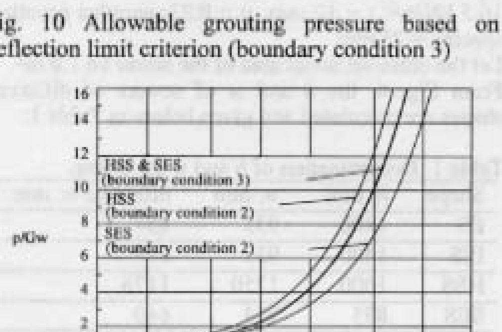

Fig. 11 Allowable grouting pressure based on buckling (boundary conditions 2 and 3)

It is clear that for the cross-sectional area and material properties chosen, semielliptical-shaped sewer lining can sustain highest amount grouting pressure. This conclusion, however, may not hold for linings of all sizes.

12 CONCLUSIONS

The proposed design curves can be used in determining the allowable grouting pressure that can be applied to the lining during installation of a variety of non-circular sewer linings under various restraint set-ups.

Allowable grouting pressure becomes higher in the presence of temporary restraints during installation of linings.

REFERENCES

Pavlovic, M. N., Arnaout, S., & Seraj, S. M. 1995. Some Aspects of Composite Circular Sewer Linings Under Installation Conditions. Submitted for Publication.

Arnaout, S., Pavlovic, M. N. & Dougill, J. W. 1988. Structural Behaviour of Closely Packed Egg-Shaped Sewer Linings During Installation and under Various Restraint Conditions. *Proc. ICE (Part 2)*. 85: 49-65.

Seraj, S. M., Roy, U. K. & Pavlovic, M. N. 1995a. Structural Behaviour of Closely Packed Inverted Egg-Shaped Sewer Linings During Installation and under Various Restraint Conditions. Submitted for Publication.

Seraj, S. M., Roy, U. K. & Pavlovic, M. N. 1995b. Structural Design of Closely Packed Horseshoe-Shaped Sewer Linings During Installation. Submitted for Publication.

Seraj, S. M., Roy, U. K. & Pavlovic, M. N. 1995c. Semielliptical-Shaped Sewer Linings Under Installation Conditions. In Preparation.

Timoshenko, S. P. & Gere, J. M. 1961. *Theory of Elastic Stability*. NY: McGraw-Hill.

Water Research Centre. 1983. *Sewerage Rehabilitation Manual*. Swindon.