Tunnelling and Underground Space Technology 71 (2018) 567–578

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

Development of a novel model to estimate bedding factors to ensure the economic and robust design of rigid pipes under soil loads

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ARTICLE INFO

Keywords:
Concrete pipes
Indirect Design Method
Bedding factor
AASHTO
British standards
Evolutionary polynomial regression

ABSTRACT

Buried concrete pipes are load bearing structures that need to resist the loads imposed by the surrounding ground. The common approach to design buried concrete pipes is based on an empirical method called the Indirect Design Method, which uses the laboratory capacity of the buried pipe linked to the field capacity using an empirical factor known as the bedding factor. However, limited published studies have investigated this bedding factor or tried to improve the current bedding factor values. Therefore, this study investigated the bending moment and bedding factor for concrete pipes under soil loads by conducting a parametric study investigating the effect of the installation condition, pipe diameter, pipe thickness and backfill height. A validated finite element model has been used for this purpose. The bedding factors obtained from the analyses have been compared with the bedding factors currently adopted by the AASHTO and British Standard (BS) design standards. The results showed that the BS design standard is conservative. In addition, the AASHTO design standard has been shown not to be safe for pipes with a diameter of 0.3 m and becomes more conservative as the diameter increases or the installation quality decreases. Therefore, new bedding factor models have been proposed using the results of the finite element modelling utilising an evolutionary polynomial regression (EPR) method. The paper demonstrates that the new models could be used for the economic and robust design of concrete pipes. The proposed models in this paper have the potential to significantly reduce the costs involved in either construction or maintenance of buried concrete pipes.

1. Introduction

Buried rigid pipes are usually designed using the Indirect Design Method, which uses the field capacity of the buried pipe linked to the laboratory capacity (i.e. the pipe is tested without soil surround) using an empirical factor called the bedding factor (*BF*) as shown in Eq. (1) (AASHTO, 2016; BSI, 2010). The laboratory test is called the three-edge bearing test, which involves the pipe being supported at the invert only and loaded by a line load at the pipe crown (further details on the test can be found in Moser and Folkman, 2008). The force which causes a crack of 0.254 mm is considered as the laboratory capacity of the pipe (MacDougall et al., 2016).

$$DP = \frac{Field\ capacity}{BF} \tag{1}$$

$$Field\ capacity = W_t \times FS \tag{2}$$

where, *DP* is the laboratory capacity of the pipe, *BF* is the bedding factor, W_t is the total force applied on the pipe in the field and *FS* is the factor of safety. The total force is calculated by multiplying the overburden pressure above the crown of the pipe by an appropriate vertical arching factor. The value of the vertical arching factor depends on the burial condition (AASHTO, 2016; BSI, 2010).

As part of the present study, a review has been conducted of the British Standard (BS) (BSI, 2010) and the America Association of State Highway and Transportation Officials (AASHTO) standard (AASHTO, 2016). The review showed that the bedding factor values are significantly different between these two standards indicating considerable uncertainty in the methodology. In the BS, the bedding factor values range from 1.1 to 3.4 depending on the burial condition (BSI, 2010). However, in the AASHTO standard it ranges from 1.7 to 4.4 depending on the pipe diameter and burial condition (AASHTO, 2016). Therefore, a thorough literature review has been conducted on the design and behaviour of concrete pipes to understand the reason of this discrepancy. Surprisingly, limited published studies have investigated bedding factors or tried to improve the current design bedding factors, with only two recent studies being found on bedding factors (MacDougall et al., 2016; Petersen et al., 2010). MacDougall et al.

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http://dx.doi.org/10.1016/j.tust.2017.11.009
Received 1 March 2017; Received in revised form 30 October 2017; Accepted 1 November 2017

Nomenclature

DP (kN/m)	laboratory capacity of the pipe
BF	bedding factor
W_t (kN/m)	total force applied on the pipe in the field
SW95	well-graded sand with a degree of compaction of 95% of the Standard Proctor test
SW90	well-graded sand with a degree of compaction of 90% of the Standard Proctor test
SW85	well-graded sand with a degree of compaction of 85% of the Standard Proctor test
ML95	sandy silt with a degree of compaction of 95% of the Standard Proctor test
ML90	sandy silt with a degree of compaction of 90% of the Standard Proctor test
GP90	poorly graded gravelly sand with a degree of compaction of 90% of the Standard Proctor test
f'_c (kPa)	compressive strength of the concrete
E_c (kPa)	modulus of elasticity of the concrete
υ	Poisson ratio
γ (kN/m^3)	unit weight of the soil
c (kPa)	cohesion of the soil
ϕ'(°)	angle of internal friction of the soil
K	modulus number
R_f	failure ratio
n	modulus exponent
r (m)	radius of the pipe measured to the centre of the pipe wall
VAF	vertical arching factor
H (m)	backfill height
D_{out} (m)	outside diameter of the pipe
D (m)	inside diameter of the pipe
t (m)	wall thickness of the pipe
CD	coefficient of determination

(2016) investigated the bedding factor for 0.6 m and 1.2 m inside diameter concrete pipes buried using the AASHTO Type 2 installation condition (i.e. the pipe is well supported in the haunch zone) under the AASHTO truck load and deep soil fill using experimental based studies. A large test pit was used for the pipe tests using an AASHTO truck load with depth of burial of 0.6 m and 1.2 m. In addition, test was also performed in a biaxial cell on the 0.6 m diameter pipe to simulate the case of a pipe buried in an embankment condition under deep burial fill. The pipe was tested by applying a maximum pressure of 700 kPa. MacDougall et al. (2016) found that the bedding factors recommended in AASHTO (2012) and AASHTO (2013) for soil load and traffic load are conservative, where the ratio of the recommended bedding factor to the obtained bedding factor ranged from 1.17 to 2.56. However, the MacDougall et al. (2016) study did not investigate the bedding factors for other AASHTO installation conditions (i.e. Type 1, Type 3 and Type 4), nor did it study the effect of the pipe diameter and pipe wall thickness on the bedding factor. Petersen et al. (2010) investigated the bedding factors of buried concrete pipes under the AASHTO truck live load using three-dimensional finite element modelling, where a single axle load was considered with a maximum tyre stress of 683 kPa multiplied by a dynamic impact factor. The bedding factors were derived under traffic load only by subtracting the bending moment due to backfill soil pressure. Therefore, the bedding factors obtained were only for live loads. The conservatism of the AASHTO soil load bedding factors is due to the fact that these bedding factors were derived using the SPIDA finite element program (MacDougall et al., 2016). SPIDA adopts a Heger pressure distribution which, unfortunately, does not simulate the correct soil pressure distribution around the pipe (MacDougall, 2014) and leads to a very conservative design of buried concrete pipes (Allard and El Naggar, 2016). Hence, the AASHTO soil load bedding factors should be updated to enable more economical and robust designs of buried pipes.

In summary, based on this review, it can be concluded that the current AASHTO bedding factors are derived based on an inaccurate assumption of the soil pressure distribution. This inaccurate soil pressure distribution provides inaccurate designs, as demonstrated by MacDougall et al. (2016). In addition, the review showed that different values of bedding factor are considered in the ASSHTO standard and the BS, although the installation conditions are approximately similar. This indicates that there is considerable uncertainty in both design standards. Hence, it is necessary to do an extensive study based on a robust methodology to investigate the bedding factors and clarify the aforementioned issues. This could help future designs of buried pipes to be more economic and provide more confidence in the design methodologies. Therefore, the present study aimed to:

1- Develop a robust finite element model to predict the bending moment in the pipe wall under an applied soil load. Developing a valid model to predict the bending moment in the pipe wall is important in this study as the bending moment is used to calculate the bedding factor (Petersen et al., 2010; Young and O'Reilly, 1987).
2- Study the effect of installation condition, backfill height, pipe diameter and pipe wall thickness on the maximum bending moment in the pipe wall under soil loads.
3- Investigate the sensitivity of the soil load bedding factor to the parameters mentioned in point 2.
4- Develop surrogate models to predict the bedding factor and enable a robust and economical design of concrete pipes under different installation conditions.

2. Current practice to determine bedding factor values

The bedding factor depends on the installation condition of the buried pipe (AASHTO, 2016; BSI, 2010). In the AASHTO standard (AASHTO, 2016), there are four standard types of installation depending on the quality of the backfill. Type 1 is the highest quality where the pipe is fully supported in the haunch area while Type 4 is the poorest quality where the pipe is installed directly on the native soil with poor compaction provided in the haunch zone. Furthermore, the bedding factor value in the AASHTO standard depends on the diameter of the pipe. Fig. 1 shows the condition of the haunch and bedding soils for each installation type. Table 1 shows the soil load bedding factor values currently adopted in the AASHTO standard (AASHTO, 2016).

The bedding factors used in the BS (BSI, 2010) also depend on the installation quality, but are independent on the diameter of the pipe.

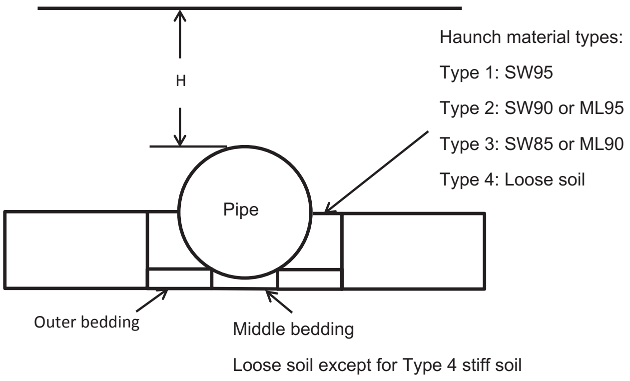

Fig. 1. AASHTO installation types (AASHTO, 2016) (Note: SW is well-graded sand or gravelly sand; ML is sandy silt).