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EARTH PRESSURE DISTRIBUTION AGAINST RIGID PIPES UNDER VARIOUS BEDDING CONDITIONS

Full-scale field tests in sand

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ABSTRACT

The factors that affect the magnitude and distribution of the earth pressure around the circumference of a rigid pipe can be divided into two main groups: soil-dependent and structure dependent. The soil-dependent factors are mainly related to the stress-strain characteristics of the natural soil and the back-fill, while the structure-dependent factors are related to the geometry of the total structure, for example the geometry of the excavation, height of the fill, diameter of the pipe, type and geometry of the foundation/bedding, and placement and compaction of the back-fill.

The objective of this study was to investigate the distribution of earth pressures against rigid buried pipes under various bedding conditions. The study includes a literature survey, an extensive series of full-scale field tests in sand and an analysis. Results from the field tests are compared with those obtained by classical semi-empirical theories, analytical models and the most recently developed direct numerical design methods.

The full-scale field tests contained tests of poor as well as good bedding and side-fill conditions. Furthermore, tests were performed where the induced trench concept was used in order to reduce the magnitude of the vertical load carried by the pipe. The soft inclusions used for the induced trench installations were mineral wool insulation mats. Such mats were placed above as well as below the pipe. The most favourable location of the mat was found to be under the invert of the pipe.

A parameter study showed that the maximum bending moment in the pipe wall can be reduced with about 70% for a case with a soft cushion under the invert, if the cushion is at least as wide as the external diameter of the pipe. At the same time the pressure from the soil above the crown carried by the pipe will be drastically reduced due to favourable positive soil arching above the pipe.

Keywords: earth pressure, rigid pipes, soil mechanics, non-cohesive soils, earth pressure cell, field tests, stress-strain, numerical simulation.

CONTENTS

SUMMARY

Introduction

Due to the expansion of the swedish sewage and storm water pipe systems during the 70:s there will, within the near future, arise an increase in the rehabilitation and maintenance needs for these systems. In order to be able to reduce the costs for these very expensive operations, there is a need for better knowledge on how to construct better pipe systems with greater durability.

The most common earth load methodologies used in today's pipe design were developed during the first decades of this century. In the design process several simplifications and assumptions were made concerning the magnitude and distribution of pressures. These methods are, therefore, not very suitable for detailed analysis of soil-pipe interaction problems. Modern and feasible methods of design have in a more advanced way to be able to take soil-pipe stiffness effects and bedding geometries into account.

The objective of this study was to investigate the distribution of earth pressures against rigid buried pipes under various bedding conditions. The study included a literature survey, an extensive series of full-scale field tests in sand and an analysis. The results from the field tests were compared with those obtained by classical theories, analytical models and the most recently developed direct numerical design methods.

The structural response of a pipe is very much dependent on the supportive capacity of the soil surrounding the pipe. A rigid pipe founded on a firm trench bottom surrounded by a loose settling back-fill will be subject to vertical stresses at the crown and at the invert. The pipe will, therefore, carry a larger load than that correspon-

ding to the weight of the overlaying soil. This, in combination with a poor lateral support, might lead to structural collapse of the pipe. However, the better the supportive capacity of the soil all around the circumference of the pipe, the more favourable the total load situation will be. Even though the supportive capacity of the soil is good, the vertical loads acting on the pipe can be of such magnitudes that the structure is in danger. For such cases, the vertical loads can be reduced by the installation of soft inclusions in the soil in order to provide for positive arching effects in the soil above the pipe. This type of installation is called an induced trench installation. Such installations, as well as normally embedded pipes, are studied herein.

Load theories

Load theories used for the the design of pipes can be divided into three main groups; these are:

- ▷ empirical and semi-empirical models
- ▷ analytical models
- ▷ numerical models

Empirical and semi-empirical models

The most common semi-empirical model is the one developed by Marston and Spangler (Krizek et al., 1971). The main principle of design according to this method is the calculation of the vertical load at the crown of the pipe, making appropriate assumptions for the load distribution at the crown, at the invert along the foundation and in the horizontal direction at the spring line. The magnitude of the vertical load is dependent on the weight of the soil prism above the pipe and the load transfer between this prism and the surrounding soil. Depending on the direction of the relative deformations between the soil prism above the pipe and the surrounding soil either a positive or negative arching effect is obtained, where positive arching is favourable for the pipe, in that it leads to a load reduction in the vertical direction.

The Marston/Spangler theory has been the object of numerous investigations, since it involves some rather crude assumptions regarding the magnitudes and directions of the stresses between the soil prism above the pipe and the surrounding soil. Some of these investigations have led to the original version of the theory being simplified in order to avoid some of the uncertainties of the method. Janson (1965) suggested such a simplification, which now is incorporated in the Swedish design code.

The other semi-empirical models used in this study are the Vaslestad theory (1990), the Christensen theory (1967), the German design code ATV A 127 (1984), the Danish design code (1986), a simple model presented by Heger (1982), and the pressure distribution presented by Olander (1950), which was advanced by Smith (1978).

Analytical models

The analytical methods used in this study are the one-dimensional, elastic approach by Voellmy (1937) and the Burns and Richard method (1964) for a circular elastic pipe deeply buried in a weightless, homogeneous, isotropic and linearly elastic soil. The Burns and Richard method is, however, in this study used in the form presented by Höeg (1966).

Numerical models

Two different numerical models have been used in this study, both of which can be used for direct design of pipes. These are the CANDE (Culvert ANalysis and DEsign) program, presented by Katona (1976), and the SPIDA (Soil-Pipe Interaction Design and Analysis) program, presented by Heger (1982). Both these programs make use of the soil model presented by Selig (1988).

Soil properties

The full-scale field tests were carried out in an abandoned sand pit. The geological formation of the site is a glaciofluvial delta built up mainly of a uniformly graded medium sand. In order to be able to obtain information about all soil parameters needed for the various load theories, an extensive laboratory investigation was performed containing standard geotechnical tests, as well as oedometer and triaxial tests. Based on these investigations, the stress-strain and strength parameters are all expressed in terms of the void ratio.

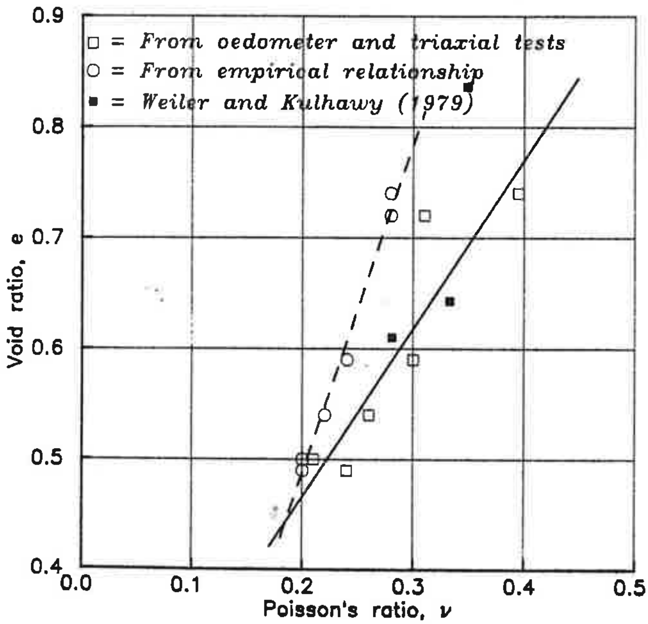

Figure S.1 *Poisson's ratio for Gråbo sand and a filter sand at various void ratios.*

Of special interest, for the design of the earth pressure cell system and in order to achieve complete compatibility between the various soil moduli, was the Poisson's ratio. Therefore, a new approach for the determination of Poisson's ratio is suggested based on well-known stress-strain relationships. In Fig. S.1, the variation of Poisson's ratio is given as a function of the void ratio for the sand used in this study compared with results obtained by Weiler and Kulhawy (1979) for a filter sand.

Measuring equipment

The earth pressures measured in the full-scale field tests were measured by means of pneumatic, Glötzl, earth pressure cells. For the design of the earth pressure cell system, laboratory, as well as numerical simulations, were performed in order to make sure that the chosen system would work satisfactorily for the measurement of the contact stresses between the soil and the curved rigid surface of the pipe. In the study different earth pressure cell theories for the behaviour of a cell installed in a semi-infinite media, as well as in a contact stress situation, are discussed.

For the measurement of the change of pipe diameter in the full-scale field tests, a specially designed telescopic rod with an ordinary analogue dial gauge was designed.

Settlements of the back-fill, trench bottom and pipes were measured using bench marks extended through the fill; protected by bellow hoses in order to reduce the effect of shaft friction from å settling back-fill.

Full-scale field tests at Gråbo

The full-scale field tests of this study were performed on reinforced, circular concrete pipes of type GERMAX ϕ600 Type B with an external diameter of 0.74 meters.

The field tests can be divided into two main groups. One group contained normally embedded pipes where the quality of the bedding and compaction of the side-fill was varied. The second group contained test sections where the induced trench concept was used, with either a soft inclusion above the crown of the pipe or a soft inclusion below the invert of the pipe. All together, ten different tests sections were studied having the same basic geometries, such as height of cover above the crown (3 m), width of trench bottom (3 m) and slope of trench walls. Five of these tests were run over a period of about eight months and the other five tests covered a period of about twelve months. Figure S.2 shows one of the test Sections during construction immediately after the installation of the pipes.

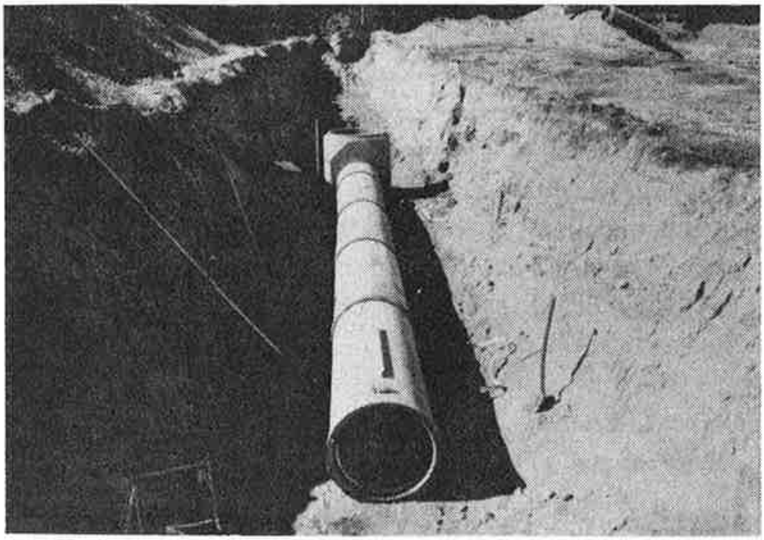

Figure S.2 *Photograph during the construction of one of the test Sections.*

Comparison between measured and theoretical values of earth pressures

The earth pressures obtained in the full-scale field tests were compared with those calculated by the various load theories. Furthermore, the corresponding pipe moments and thrusts were calculated, based on the earth pressures obtained by some of the various models.

Generally, the pressure distribution used for pipe design plays an important role for the calculated internal forces and moments in the pipe. The bedding angle has a major influence on the moment distribution within the pipe. A narrow bedding angle means large stress concentrations at the invert and will also result in large moments at the invert. Therefore, pipes must be designed for realistic bedding angles and, furthermore, the quality of the construction in the field has to be carefully controlled, so that the engineer's assumptions about the bedding angle are satisfied by the contractor.

The semi-empirical theories discussed in this study gave, for the geometries investigated, more or less conservative earth pressures. The most powerful semi-empirical method for design seems to be the German ATV-method, which is the only of these methods that can take soil-pipe stiffness effects into account in the design process. The Vaslestad theory can, however, also yield realistic earth pressures. The uncertainty of this method lies in what value of which roughness ratio to use.

The classical theory by Marston and Spangler gave very conservative earth pressures.

The analytical method by Höeg cannot take the bedding conditions into account and, hence, the bending moments in a pipe based on this method will be underpredicted.

The CANDE-program assumes a very favourable bedding condition in the level two version. This leads to an unrealistic earth pressure distribution.

The earth pressure distribution obtained using SPIDA seems, however, to be fairly reasonable. In Figure S.3, the radial earth pressure distribution and pipe deflections calculated using SPIDA are compared with those measured in the field for one of the test sections. Furthermore, the direct design approach incorporated in SPIDA seems to be a very promising and powerful design tool.

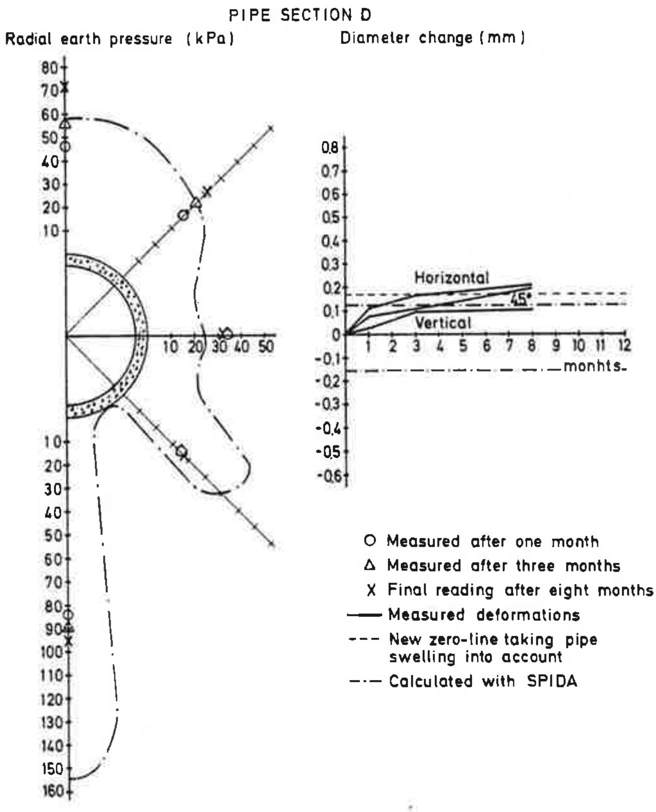

Figure S.3 *Radial earth pressure distribution and pipe deflections for test Section D.*

The results obtained for the test sections, where the induced trench concept was used, all show very favourable positive arching effects due to the soft inclusion. In the full-scale field tests, the soft inclusions consisted of mineral wool insulation mats with a well-defined stress-strain relationship. The tests, together with a parameter study, showed that the most favourable location for such a soft inclusion is under the invert of the pipe. For such an installation, the pipe support will be better with increasing settlements of the pipe into the cushion, due to the larger area over which the reaction force will be distributed. The arching effect will increase with increasing cushion width, and due to the positive arching the lateral pressures at the spring lines will increase as well.

When the induced trench concept is to be used with a soft cushion under the invert, the pipe installation has to be designed taking the vertical settlement of the pipe into the soft foundation into account. The pipe installation must be designed so that it settles down to its intended level. Therefore, a method is suggested for the calculation of such a settlement due to the weight of the pipe and the weight of the soil carried by the pipe.