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DESIGN OF BURIED PIPELINES IN DEFORMING GROUNDS

CALCUL ET EXECUTION DE TUYAUX ENTERRES DANS LES SOLS DEFORMANTS

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SYNOPSIS: In principle all pipelines are to be considered as pipelines in deforming ground, either because the surrounding ground or backfilling settles or the pipe gives way to the overburden pressure. This is the base on which design and execution of pipelines has been carried out in Denmark for many years and around which the Danish Code of Practice for foundation of various types of pipelines has been established. It is not a single Code, but a frame of Codes each covering a special type of pipeline such as concrete pipes, plastic pipes, gas pipes, district heating pipes, offshore pipes, drain pipes etc. This paper deals with the principles laid down in the Danish Codes which serve as guidelines for any engineer whether he or she is manufacturing the pipes or designing a pipeline, or executing the work as a contractor or performing the construction supervision. Special attention is given to design of both circular rigid pipes and flexible pipes. The use of FEM for more complex pipeline geometries is commented. The relatively few failures of installed pipelines in Denmark proves the balanced level between design rules, safety application, construction and control.

FUNDAMENTAL REQUIREMENTS

The pipes shall be manufactured, designed and placed in the ground in such a way that

- sufficient strength to resist the imposed loads is achieved
- sufficient resistance against mechanical, chemical, thermal and biological impact is achieved
- sufficient lifetime for the pipeline is ensured.

These requirements are achieved by proper pipeline design based on soil investigations, careful selection and control of the pipe material, and checks on the installation as required by the circumstances.

PIPE MATERIALS

Typical materials for pipelines are unreinforced or reinforced concrete, various types of plastics such as PEL, PEM, PEH, PP, PVC, ABS, GRP (fibre-reinforced polyesters) etc. and various qualities of steel. The pipe profile is generally circular, but concrete pipes may have a base or a rectangular shape.

PIPELINE INSTALLATION IN DITCH OR TRENCH

The cross section of the pipe ditch or trench should be shaped in accordance with the selected excavation method, the pipe dimension and type, depth below ground level, soil and groundwater conditions, load conditions on ground close to trench and the number of pipes in the trench.

For the backfilling the Codes distinguish between backfilling below the pipe, around the pipe and above the pipe with corresponding different requirements for quality of fill materials and compaction of fill. The bottom fill layer serves as the pipe base in which bedding of fittings and pipe takes place and a sand or clay material without sharp stones or cobbles is used. The surrounding fill serves as support for the pipe sides and carries the dead load from the fill above and the live load on the ground. The excavated soil material may be used provided it fulfils the same requirements as for the bottom layer and can be compacted to the required degree of compaction which depends on the loading. The fill above the surround fill is usually the excavated soil material compacted to serve the purpose as a base for live load on ground.

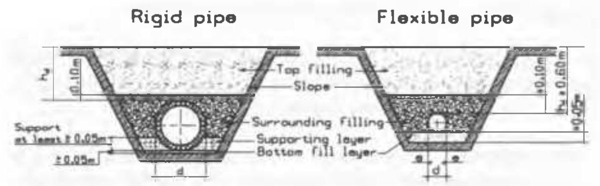

Fig. 1. Typical pipeline cross sections

For offshore pipelines special requirements in terms of friction and density for the backfilling are required in order to prevent buoyance of the pipe.

CONTROL

A pipeline project will be controlled within alignment geometry, pipe and filling materials, excavation, installation, compaction and final performance monitoring. The level of control depends on the project and installation conditions and is divided into 3 control categories ranging from a limited control over a normal control based on spot checking to an intensified control by systematic testing and checking of each of the above elements. Details of the control measures are laid down in the Codes for each of the 3 control categories.

DESIGN

The fundamentals for the design of a pipeline is to define

- installation method
- design load
- safety level within limit state design method
- pipe stiffness compared to soil stiffness
- pipe failure mechanisme to be used with the calculation model.

Design load

Two load types have to be taken into consideration, namely *permanent load* such as soil load, groundwater pressure and unit weight of pipe and *variable load* such as uniformly distributed live load, traffic load and internal pressure in pipe.

For *rigid pipes* such as concrete pipes the characteristic vertical load of fill above the pipe is determined by $v_j = \lambda \cdot \gamma \cdot h_d$ kN/m² where h_d is the soil height above the pipe, and the relief effect from the lateral pressure is included in the use of the net earth pressure coefficient λ given as

$1.62 + 0.5\ h_d/d + 0.3\ d/h_d$	for control category 1
1.60	for control category 2
1.4	for control category 3
1.0 for bored minitunnels	

The unit weight γ of the fill is 21 kN/m² above groundwater level and 11 kN/m² below.

The vertical load is distributed over the exterior pipe diameter d while the reaction width is 0.5 d for circular pipes, 0.7 d for circular pipes with improved bottom fill layer, d for bored minitunnels and base width for pipes with a base. The lateral load is distributed over the entire height of the pipe. For *flexible pipes* such as plastic pipes the vertical fill load is the effective overburden q_v while the lateral pressure is expressed as $q_h = 0.4\ q_v$ both acting over the entire width or height of the pipe. The groundwater pressure shall be added to q_h as well as q_v.

Among the *variable loads* the traffic load v_t from truck axles or railway boggies including impact factors is computed for pipe top level by means of an elastic distribution.

Safety and partial coefficients

The calculations are carried out within the limit state design principles, and comprise an analysis of the ultimate limit state (ULS) associated with a collapse of the pipe and a calculation of the serviceability limit state (SLS) concerning deformations, movements or deflections of the pipe.

In the ULS different load cases are examined and the corresponding partial coefficients are applied, on permanent load $\gamma_f = 1.0$ and on variable load $\gamma_f = 1.0$ or 1.3 depending on the load combination.

The partial coefficients on the pipe material properties depend on pipe stiffness and control category. For *rigid pipes* of reinforced and unreinforced concrete pipes the partial coefficients for the materials vary with the level of control from $\gamma_m = 1.5$, 1.4 to 1.3 for control category 1, 2 to 3 provided the bearing capacity of the pipes has been evaluated by full scale testing. For reinforced pipes designed solely by calculation the partial coefficients for concrete $\gamma_c = 1.8$ and 1.7 and for reinforcement $\gamma_s = 1.4$ and 1.3 are used for control category 2 and 3 respectively.

For *flexible pipes* $\gamma_m = 2$ is used on the characteristic long-term values of failure stress and modulus of elasticity of the pipe material unless another value is defined by the nominal strength of pressure pipes, e.g. $\gamma_m = 2.5$ for PVC, 1.3 for PEH. For the soil and fill material the design value of the oedometric modulus is defined as $K_d = K/\gamma_m$ or $K_d = K\gamma_m$ depending on worst condition. This is relevant only for flexible pipes, where $\gamma_m = 2$ is used on the oedometric modulus.

In the SLS partial coefficients equal to 1.0 are used all over.

CALCULATION OF PIPE BEARING CAPACITY

For *rigid pipes* the pipe bearing capacity will be based on a calculation of stresses determined for the actual laying and bedding conditions and compared with the stresses computed for a declared failure load.

For concrete pipes the characteristic bearing capacity in the soil is determined by $r_k = k \cdot F_k/d$ kN/m² where F_k is the declared minimum failure load from the load testing and k is the load factor, i.e. a ratio that accounts for different load distributions in the testing machine and in the soil. This calculation method requires load testing conditions similar to those in the trench in terms of development of cracks and distribution of shear stresses and moments. The method is applied primarily for unreinforced concrete pipes, but can also be used for industrially produced reinforced concrete pipes in lieu of a calculation according to the theory of plasticity.

The design pipe bearing capacity is determined as r_k/γ_m kN/m² and compared to the design load v_d in the trench: $v_d \le r_k/\gamma_m$.

For *flexible pipes* the calculation is only necessary in case of pipe materials or laying conditions beyond general experience.

The pipe bearing capacity will be calculated in a design state regarding stresses and deformations as outlined below for circular plastics pipes. The pipe stiffness $S_R = EI/r^3$ is determined by the flexural rigidity EI and the radius r of the pipe wall. For the calculation it is introduced as a long-term or creep value S_{Rc} which will usually be much less than the short-term value. The pipes are divided into two groups, relatively rigid pipes with $S_{Rc} > K/18$, and more flexible pipes with $S_{Rc} < K/18$.

For the relatively rigid pipes the circular cross section is assumed to deform into an ellipse and the critical outside pressure on the pipe is determined as

$$q_{cr} = q_{el} \cdot f_1(\beta) = \left(\frac{1}{6}K_d + 3S_{Rc}\right) \cdot \frac{1}{1+\beta}$$

where $$\beta = \frac{r}{e} \cdot \frac{q_{el}}{f_d} \quad ; \quad r = \frac{1}{2}(d - e)$$

and f_d is the design bending or hoop stress, e is the wall thickness and r the mean radius of the pipe wall. Both K_d and S_{Rc} are design values.

For the more flexible pipes the deformation depends on the loads imparted during the installation and the deflection curves can hardly be calculated in advance. The critical outside pressure is then fixed as

$$q_{cr} = q_{el} \cdot f_2(\beta) = \sqrt{2 \cdot K_d \cdot S_{Rc}} \cdot \left(\sqrt{1 + \frac{\beta^2}{4}} - \frac{\beta}{2}\right)$$

where β is defined as before. The bearing capacity criterion for both cases to provide sufficient safety against buckling of the pipe wall is $q_{cr} > q_v + \gamma_{f1} \cdot p_t + \gamma_{f2} \cdot p_u$ kN/m² with partial coefficients $\gamma_{f1} = 1.3$ on the traffic load effect p_t and $\gamma_{f2} = 1$ on a possible suction p_u in the pipe, or vice versa if $p_u > p_t$. For pipes below the ground water table it is further required that

$$\left(h_w + \frac{d}{2}\right)\gamma_w + \gamma_{f2} \cdot p_u < \frac{3S_{Rc}}{1 + \frac{r}{e} \cdot \frac{3S_{Rc}}{f_d}}$$

The deformations of the two groups of flexible pipes are evaluated in a similar semi-empirical way.

CONCLUDING REMARKS

For complex trench and/or pipe geometries cut-and-cover tunnels and special soil and/or ground water conditions the application of FEM has proved successful in the understanding of the loading impact on the stress and deformation development.

Among the relatively few failures of newly installed pipelines in Denmark, the lack of sufficient site investigations and/or proper control during pipe installation or backfilling is more often the reason for the failure than the pipe strength or stiffness. However one shall still remember that the administration of the rules and regulations laid down in the outlined codes of practice requires sufficient technical skill in order to avoid any malfunction or collapse of an installed pipeline.

REFERENCES

Soc. Danish Engrs. (1986), Code of Practice for Laying of Underground Flexible Pipelines of Plastic (DS430) / Code of Practice for Laying of Underground Rigid Pipelines of Concrete etc. (DS437).