THE UTILIZATION OF PLASTIC PIPE FOR SUBMARINE OUTFALLS — STATE OF THE ART

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ABSTRACT

During the last 25 years, a great number of submarine pipelines have been built in Scandinavia. They are all a result of intensive activity in the field of environmental control, the consequence of which has often been that the last purification step in the wastewater treatment process has been considered to be the dilution of the residual waste into the ocean. Efforts have been made to develop a new piping technology which would allow great depths and points situated far off-shore to be reached, where the risk of problems due to floatable materials flowing back to the shore is insignificant. It has been regarded as especially essential to find a technique which would enable a cheap and rapid procedure for pipe submersion even far off-shore and in heavy sea conditions. The reason for this is that a major proportion of the cost of a submarine pipeline relates to submersion work. Additional requirements were that the pipe material should withstand sudden and even exceptional wave forces and also permit uneven settlements as well as movement of sediment on the sea bed. Thus, the aim has been to develop a highly flexible pipe.

The paper presents the state of the art by referring to a submarine outfall project implemented in Sweden 1985. Some need for further development is also discussed.

KEYWORDS
Submarine outfall; plastic pipe; polyethylene; polypropylene; flexible pipe; sewage discharge; marine disposal.

SUMMARY OF THREE DECADES OF DEVELOPMENT AND EXPERIENCE

In this paper the discussion is limited to outfall pipes which, in terms of permissible material strain, can be looked upon as flexible. It is essentially this flexibility which forms the basis of a completely new design philosophy for submarine outfalls that differs radically from the classic rigid pipe design. Designers are well aware of the fact that structures which are subjected to loads that are difficult to predict exactly in terms of both way of application and magnitude, are preferably equipped with a large number of joints. This gives the structure a certain degree of flexibility. A submarine outfall pipe is a textbook example of a structure for which the loads caused by waves, currents, erosion, etc., are difficult to predict. Consequently, the use of a rigid structure requires the application of extremely large safety
factors or, otherwise the pipe has to be positioned deep down in the bottom sediment where the effect of the stochastically appearing loads has as far as possible been eliminated. This often leads to a very expensive structure. The general idea of using the flexible piping technique is to create a more optimal structure in terms of both implementation cost (particularly the submerging technique) as well as the cost of operation and maintenance. By using the flexible piping technique, which invariably tends to be less expensive and safer than the rigid piping technique, it is also normally possible to reach deeper depths and longer distances out from the coast. Here the dilution effect is much greater and the risk of floatables being returned to the shore is greatly reduced. This also means that pretreatment of the sewage on land can be decreased, thereby providing an environmentally sound method of disposal at the lowest total cost (Janson and Larsen, 1979).

The large diameter pipe materials which in terms of flexibility behave more or less as though they were equipped with an infinite number of joints, are mainly polyethylene of high density (HDPE) and of medium density (MDPE). For outfalls which require special high temperature resistance, polypropylene (PP) is a feasible alternative (Janson, 1978).

Both HDPE and PP were developed in the early 50s, and became commercially available in 1956. The major contribution to the early knowledge of these materials, particularly as far as long-term strength is concerned, was made by Hoechst AG in Germany (Gaube 1959; Gaube et al., 1976). The first 10 years were marked by applied research and development, and during this period the first flexible submarine outfalls were constructed in Scandinavia, although mainly in diameters of below 500 mm.

The decade from 1966 to 1976 was the period during which civil engineering activities in Scandinavia were directed at development of the flexibility philosophy in more detail (Janson 1974, 1975). In this period the first 1 m diameter HDPE outfalls were constructed mainly for discharging effluent from pulp mills. During the same period a great number of municipal pressure sewage submarine transmission pipelines were constructed both in Scandinavia and in Europe to meet the demands of the extensive environmental protection programme.

The last decade, from 1976 up to the present time, has to a great extent been marked by the development of improved polyethylene resins, which are less sensitive to thermal oxidation, have a better long-term strength and higher temperature resistance (Janson and Björklund, 1976, 1980; Gaube et al., 1985). Particular mention should be made of the medium density grades (MDPE) which are in general better able to meet the requirements imposed on them than the previous HDPE grades. During this period the diameter range for HDPE and MDPE was increased to 1.2 m, and in some extreme cases to 1.6 m, at the same time however, limit the internal pressure to about 4 bars. One recent project is described in the next section as the basis for a state of the art report concerning flexible submarine piping technique.

A RECENT CASE STUDY

The following project has been chosen as an example to describe the state of the art for flexible submarine outfalls, since it provides a good opportunity, in the same project, to compare the design philosophy and criteria applied in the early 70s with those applied today.

In 1972, a 5 km long submarine outfall with a diameter of 1 m was constructed at Värö Pulp Mill, situated on the west coast of Sweden and discharging up to 2 m³/s of pretreated wastewater by pumping it out into the Kattegatt at a pressure of 3 bars. The outer part of the outfall has a 1 km long diffuser lying at a depth of 16 m. In 1985, after 13 years of operation, successively increasing energy costs made it feasible to decrease the need for pumping by adding an additional pipe, thereby creating a dual outfall. The decrease
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in pumping costs would in this case mean a pay-off time for the new outfall in the range of 10 years. In addition, increased operational safety would be achieved as there was reason to believe that it would be difficult for the existing HDPE grade (Hoechst GM 5010) to withstand the higher effluent water temperatures (up to +45°C) successively being introduced as a result of a general industrial water conservation programme that was being implemented, while at the same time maintaining the same high pressure.

Several new grades were found to meet both the manufacturing and the operational requirements, among which were the Hoechst GM 5010 T2, Hüls' Vestolen A 5041 R, and the Unifos MDPE grade DGDS 0909. It was the latter which in this case proved to offer the cheapest alternative, due partly to the fact that the pipe could be manufactured in a factory near the sea not more than 260 km from the mill site, thus providing ideal conditions for towing the pipes in long lengths (400 m each) from the plastic pipe factory directly to the pulp mill.

As the pipe material was of a new type, which meant that no experience was available from large diameter pipe extrusion, procurement was preceded by pilot manufacture and testing. In order to determine the long-term strength of the pipe material a new method was used (Janson, 1983) in which the relation between loading time and strain increase (creeping) was studied with the stress as parameter. The design criterion was then based upon the stress which after 50 years' loading time at a given temperature should give a maximum strain of 5 %. This is a more practical way of establishing the design stress than the one employed today, which involves searching for the time to failure. In particular when using the new MDPE grades, failure is preceded by considerable deformation, which means that the time to break can be up to one logarithmic time decade longer than the time it takes to reach a workable strain of say 5 %. As an example based on international standards, the test requirement is that the time to break at a stress of 3.9 MPa and a temperature of +80°C shall not be less than 170 hours. Our pilot study showed that the 1 m diameter MDPE pipe made of DGDS 0909 had a strain at that time exceeding 5 %. After 2 000 h the strain was 11.1 %, after 3 800 h 11.6 %, after 6 200 h 11.8 %, and at the time of writing there has still been no failure, even though the pipe has now been tested for 10 000 h and the strain in the pipe wall is unpractically high, or about 12 %. This helps to show the importance of introducing a modified long-term strength philosophy when using the new polyethylene grades. As a result of the pilot study it was found that a design stress of 3.4 MPa constantly acting at a temperature of +45°C would give a maximum strain of 5 % after 50 years. The safety factor against failure is then estimated at 1.8 based upon the relation between burst stress and design stress.

As regards the internal and external loading conditions for the pipe, a considerable amount of the experience gained on the old flexible outfall was utilized when designing the new one. Thus the flexibility philosophy was applied extensively in the case of both pipes, resting as they do on the sea bottom directly exposed to wave forces, currents and sediment movement. To begin with the internal operational conditions, pressure surges will occur in the pipe in the event of a sudden pump stop, thereby giving rise to underpressure in the pipe. This pressure drop will propagate along the pipeline producing an ovalization of the ring section of the pipe. This ovalization must be limited if buckling of the pipe is to be prevented. Even in the case of the old pipe, it was found that the anchorage weights surrounding the pipe had an important role as ring stiffeners. For the new pipe, which has a material with a lower E-modulus than the old one, the calculations showed that the distance between the anchorage weights was not allowed to exceed 3.6 m. In addition, it was found feasible to introduce an elastic movement ability for the weights to follow the pipe diameter changes without losing any of their firm fixation to the pipe.

Another important design condition is connected to the fact that the anchored pipeline is not stable in the event of air or gas entering the pipe to more than 25 % of the cross-section. (A full air fill would mean that the pipe would float up to the surface; a condition which is just created for facilitating
a simple submerging procedure). Thus both pump entrance and by-pass arrangements in the pump station were originally designed for preventing air from entering the outfall. The experience gained from operating the old pipe was very good, and the question was whether or not this could also be due to the fact that the pipe bed for the old pipe was made very straight, giving virtually no variations in the vertical alignment of the pipe. The idea was that if there were individual high points along the alignment, gas or air could be collected and accumulated there, particularly during low flow conditions or during longer periods of operational shutdown. Based on experience concerning the actual position of the old pipe, it was decided to minimize the pipe bed preparation for the new pipe, thereby saving a lot of money. It was thus stipulated that no bottom point of the pipe should be allowed to be placed above any upstream summit of the pipe.

As regards the external forces, these originate mainly from waves, currents and changes in the sediment. The significant wave height in deep waters with a 100 year return frequency is estimated at 4.5 m having a wave length of 110-120 m. Measurements since 1970 appear to verify this estimate. The typical characteristic of the flexible outfall is that it can be designed for a wave height much smaller than the "maximum" wave. Instead, very small oscillating movements of the pipe are accepted for waves exceeding the design wave. Depending upon the direction of the outfall in relation to the most dangerous wave direction, it is always possible to find the required weight of the pipe which for very large waves will move the pipe temporarily expressed as amplitudes around the centre line of the pipe, but never move the pipe permanently from its designed alignment. Thus the old outfall was designed for the 2 year wave, and during its 13 years of operation it has never been damaged or permanently moved in spite of the fact that at least the 50 year wave occurred during this period of operation.

The same experience was gained in connection with the outfall from the Brazilian pulp mill Aracruz, where we also designed the 1 m diameter PP outfall for the 2 year wave. No sign of movement or failure have been reported during the 8 years of operation followed up by diver inspection each year (Björklund, 1983).

On the basis of this practical experience and vast theoretical studies, the new outfall at Väro was designed for the 1 year wave only, by checking simultaneously that the 100 year wave will not cause unacceptably large movements. It is in particular the large permissible bending strain of the MDPE up to at least 5 % which makes such a design possible today. Consequently for depths of more than 12 m, the pipe has been loaded to an extent corresponding to only 25 % of its displacement. In the surf zone, where the waves break and the water depth is 3 m, the pipe is still directly exposed to the wave forces, but here the pipe load has been increased to 60 % of the displacement.

With regard to preparation of the pipe bed, only very small measures have been taken. Thus no dredging or filling have been carried out for the new pipe. The only requirement was that the pipe should not be allowed to rest directly on stones greater than 0.1 m in diameter and that stones larger than 0.2 m should be removed for a distance of 3 m on each side of the outfall.

Other experience gained concerns corrosion of the steel bolts that keep the anchorage weights together as well as corrosion of the steel flanges which hold the 400 m long pipe lengths together at the joints. Today, use is made of normal hot galvanized steel protected with a special sacrificial zinc anode applied as a cast part of the bolt nuts. These nuts are designed for a lifetime of 10-40 years.

The manufacture, construction and installation of the 4 km long outfall connected to the existing diffuser via a Y-shaped pipe fitting took not more than 6 months. The total cost in 1985, including bottom surveying, pipe manufacturing and quality control, submerging, connections, construction control by divers and consulting services, was SEK 15 million.
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NEED FOR DEVELOPMENT

The flexible submarine piping technique using viscoelastic polyolefins as pipe material has reached an advanced stage of development and most problems have been identified and solved. Thus most requirements for creating an inexpensive, safe and environmentally feasible outfall can now be met. However, a certain amount of development is still necessary if the flexible piping technique is to reach a wider market and be adopted for more general utilization.

The first problem which should be mentioned in this context is the limited pipe diameter available particularly when high internal hydraulic pressures are required at the same time. Today the largest PE pipe diameter manufactured is 1.6 m and has a wall thickness of 60 mm. This corresponds to a nominal pressure class of 4 bars at a temperature of +20°C. The maximum discharge capacity for such an outfall with a length of 4 km is almost 8 m³/s. The pressure head of 40 m is then assumed to be achieved by pumping. A population served by an outfall with this maximum discharge can be estimated at 600 000. For a normal gravity head of 5 m, the maximum population served by the outfall can only be 200 000 people.

It should be pointed out that it would be possible to achieve a much better level of environmental protection and better use of the natural purification ability of the ocean if the discharge of major sewage concentrations at one point could be avoided. It must be emphasized that pollution is a material concentration problem and that the most economically viable onshore pretreatment of sewage would be achieved if several small outfalls could be installed rather than one large one.

This is a classical optimization problem and will be given no further consideration here, but it is important to remember that application of the flexible submarine outfall technique lends itself more to the use of several small pipes than does the rigid outfall technique.

However, coming back to the difficulties involved in manufacturing very large diameter plastic pipes, the consequence of this limitation is that concrete or steel has to be chosen in those cases in which advanced sewage treatment is necessary on land and where treatment is best carried out in one plant with, as a consequence, one outfall only. Therefore, it would be advantageous to develop flexible large diameter pipes which could take hydraulic pressures of up to at least 10 bars without increasing the wall thickness, and in this way keep down the cost of the pipe. A development project along these lines has advanced successfully over the past three years in Scandinavia. The main purpose of the project was to meet the demands of the offshore oil and gas industry for flexible transmission lines and "flowlines" with very high pressures of up to 500 bars. As a spin-off effect of the technique developed, it is believed that rather inexpensive flexible medium pressure pipes can come on to the market in the near future.

The second problem which should be emphasized is the very great need for a cheap technique that facilitates the crossing of the surf zone close to the shore where heavy waves break. It is a well-known fact that trenching in surf zones of the type most common, for instance, along the Brazilian coastline is a difficult process, which in many cases can never be predicted with regard either to construction time or costs. Theoretical work aimed at finding a technical solution to the problem utilizing the flexibility of plastic pipes has recently been initiated at VBB.

The idea of the theoretical approach came from the experience gained from practical work on the burying of plastic pipes in bottom sediments. It was often found during the refilling of a trench with fine grained soil such as fine sand or silt, that the buried pipe could float up from the trench. Only by increasing the weight of the pipe to at least 40 % of the pipe displacement was it possible to keep the pipe in position in the trench. This phenomenon shows that the soil/water mixture during the refilling process behaves as a heavy liquid in which a light structure will float.
Thus by turning this observation the other way round, a heavy pipe should sink down in the bottom sediment provided the bottom soil can be transformed into a liquid. In nature this phenomenon is recognized as quicksand in which an existing water pressure makes the sand acting as a liquid dangerous for people to step on.

The theory is dealt with in the fluidized bed technique applied today in the development of modern combustion equipment (Davidson et al., 1971). By applying a jet of high-pressure water/air below the pipe, tests will show under which soil condition the pipe will be buried in the sediment by its own weight. In order to minimize the length of the active fluidized bed, it is important for the pipe to be highly flexible with no joints so that a steep S-shaped bending of the pipe can be achieved.

Another possible way of crossing the surf zone which is under investigation involves the use of the pipe jacking technique, in which context jacking is performed from a shaft on the beach. Various ways of replacing the soil with a flexible pipeline are now under discussion as a practical basis for construction tendering.

It should be concluded that a feasible method for crossing the surf zone is the most urgent development work now in progress. The investigations performed so far show, that an optimal technical solution is being approached based on an adequate utilization of the flexible piping technique.

REFERENCES


