Tolo Channel submarine pipelines, Hong Kong

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As noted in the acknowledgements I was involved in the project when the Authors were still occupied elsewhere. The options considered at the preliminary design stage included a 3 m dia. tunnel and a single large diameter bottom pulled pipeline. As noted in the paper the tunnel was rejected due to uncertainty as to the cost and time for driving through a fault in mid channel. The 2.5 m dia. pipe would, probably, have been selected if the client had been consistent in his estimates of demand and the cost of capital but pipes over 2 m dia. are near to the practical limit for the bottom pull method. What do the Authors believe are the largest practicable and economic diameters for bottom pulled welded steel pipelines?

50. The immediate precedents for the Tolo pipes were a 1.8 m internal diameter sewer outfall 2000 m long in Manila Bay where the marine mud is even deeper and softer than at Tolo and an outfall of similar size into about 60 m of water on a firmer bottom in Beirut. Complete calculations, contract documents and construction records were available for both these projects. There is no difficulty in laying a continuous welded steel pipeline by the bottom pull method on the softest possible sediments; the problems are to steer the leading end of the pipe along the chosen vertical profile and to support any armour needed to prevent damage by anchors. The most critical design parameter for a submarine pipeline, on a soft bed, is likely to be the anchor which will not be allowed to damage the pipe, the exact ways (direct hit, dragging on the surface or dragging at depth) in which this anchor may attack the pipe and the load factors to be applied to these accidental load cases. The Manila pipe is in an area where vessels of up to about 30 000 dwt frequently drag their anchors in typhoons and the pipe was designed to resist an 8 t standard stockless anchor. A sand shoulder was provided to prevent the pipe dragging sideways through the soft mud. There was no anti-corrosion coating between steel and concrete so that the steel tube and the reinforced concrete encasement could be designed to act together to resist the twin point loads from the anchor. The Tolo design started from this point, but plans to build a liquefied petroleum gas terminal close to the line resulted in the need to consider the very much larger anchors used by LPG carriers. The philosophy of relying on the concrete alone to prevent corrosion of the steel tube was also rejected. These adjustments made it necessary to revise the entire design—complete security probably required that the pipe would be laid on the alluvium and protected with armour with a substantial increase in cost. Was the probability that the pipe would be damaged, by an anchor, assessed and if so what risk or damage frequency was accepted?

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51. Another problem which has a dramatic effect on the design of large diameter submarine pipes is the risk that the outer reinforcing bar will corrode before the end of the design life. Expert opinion on this matter is changing quickly: in Manila the corrosion engineer was quite content with 40 mm cover of good quality concrete made with type V ASTM cement. At Tolo type V (and SRC which is approximately its British equivalent) was rejected owing to poor resistance to penetration by chloride ions. An outfall in Hong Kong which is due to be constructed in 1990 will have a concrete encasement similar to that used at Tolo but in addition epoxy coating to the outer re-bar cage. However, the wrapping to the steel tube will be omitted. What are the Authors' views on this debate?

52. If the line is not pulled in along the correct profile the cracks in the encasement may be wide, so the durability of the pipe depends on the control of alignment during construction. None of the bottom pulled steel pipelines, for which complete records are available, have been installed exactly according to plan. The Paper gives a very frank and useful description of the use of Hong Kong derrick lighters to steer the leading end of the Tolo pipe. The Manila line was laid high to allow for settlement when flooded, but it then settled less than expected. The Beirut pipe ploughed into the sea bed, stuck and had to be lifted. Two smaller pipes laid in Hong Kong have also run off line but without ill effect on the curvature or pull force. The Tolo pipe was pulled off a sloping launchway aligned with the vertical profile to eliminate the need for very heavy rollers to bend the uncracked pipe at the sea wall, but ploughed into the mud in mid channel. The lesson was that a soft mud bottom will not deflect a stiff pipeline, a specified external force is required to develop the underwater sag bends. It is therefore necessary to calculate both the vertical force at the lead end of the pipe at each stage of the pull and ensure that this force can be applied either from the surface, as at Tolo, or by a sledge if the bed is firm enough or by controlled buoyancy.

53. The range of stiffness and the submerged weight will cause wide variations in the vertical force needed to make the pipe follow the correct line and it is therefore necessary to monitor the level of the leading end of the pipe continuously and adjust the force as required. The survey methods adopted on the recent submarine pipelines in Hong Kong by the main contractors and Electronic and Geophysical Services Ltd, who have been responsible for all the hydrographic survey for all these projects, are levelling inside the pipe, diving on the lead end of the pipe with a sensitive pressure gauge, a trench profiler on a survey boat stationary over the line and a narrow beam echo sounder on a boat drifting slowly over the line. The simplest method is the narrow beam echo sounder with the boat's position determined from a laser beam on the line, but the other methods are useful and should be available. How will the Authors monitor and control their next pipeline?

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In answer to *Mr Osorio's* comments, a further precedent was the 2 m dia. outfall at The Hague which also had no external protection to the steel tube other than the concrete cladding. Minor corrosion might not be considered a problem in an outfall, backfilled, operating at low pressure and designed to discharge to the sea. While the Authors were not aware of any operating difficulties with these previous outfall designs, the view adopted for Tolo and for two other similar and contemporary pipelines was that the uncertainties associated with omitting the sheathing

outweighed the benefits where the pipeline was to carry water for the public supply. This view was still justified on review after construction. Special coatings to the reinforcement were considered but showed no established advantage. Any localized failure, however unlikely, would be mitigated by redistribution and would be different in effect from failure of the steel pipeline. General failure of the reinforcement was felt unlikely and as the pipeline would be buried reliance was placed rather traditionally on a 60 mm cover of dense impermeable concrete.

55. Structural design included the criterion that crack widths should not exceed 0.2 mm. This conservative approach allowed for bending radii in practice to be tighter than the specified 3000 m minimum. Some accidental and uncontrolled backfill in the tidal zone resulted in bending the pipe to a minimum radius—found by careful internal survey to be about 1500 m before correction. Alternative wetting and drying during the tidal cycle gave rise to short hair cracks in the tension side, generally at about 1 m spacings but nowhere less than about 300 mm, indicating some tension stiffening and an inherent reserve of strength. Existing cracks in the mortar lining widened on the tension side but to no more than about 1.5 mm. Tension stresses in the steel shell were likely to have been at the upper end of the range 120–180 N/mm² but in the mortar lining were probably at or less than one-third of the compressive strength.

56. Especial care was taken from horizontal alignment of the first line. Lateral correction proved possible by derrick lighter and tug only as the pipe was advanced forward during each pull. The pipe tended otherwise to slip back into the track generated by the pull. Echo sounding correlated well because stiffness of this large pipe allowed a smooth line to be drawn with confidence through the several survey points. For the second line internal survey was adopted where possible but control was also by diver inspection using the first pipeline as reference and by use of pressure sensitive cells for level. Tape measurements and sightings on a series of pencil buoys on the pipe nose end at field joints along the first few hundred metres of the pipe supplemented diver checks. Echo sounding was not used for the second pipe and if only one line had to be laid or both were to have been laid together this method might have been an option although in practice even in the calm waters of Tolo the physical record produced by echo sounding would be hard to forgo. For the next outfalls echo sounding has been specified. Water depths are great, currents high and complex. Internal survey is likely as well and the Contractor is additionally proposing video inspection by remote control vehicle.

57. Pipe strings 91 m long weighing 500 t were handled successfully at Tolo. Larger diameter pipe would be heavier and would require flatter bonding radii which in turn would influence the dredged profile and costs. Pipe up to 3 m dia. have been reported laid by bottom pull.¹⁰ The upper limit for bottom pull would be a function of cost and would vary according to circumstance, available plant and preference. Tenderers should be permitted to price alternatives.

58. Analysis was made to assess the risk of ships laid up in Tolo harbour becoming stranded above the pipe in a typhoon. While the risk was small because prevailing winds blew towards the anchorage area the top of the backfill was kept below the top of the hard soils near the landfalls. The greatest risk was that the pipe would be hooked by a large ship's anchor. Anchor strengths were assessed carefully and the conclusion drawn that to strengthen the pipe to provide complete protection to requirements would need impractically thick concrete and heavy reinforcement. To provide complete protection by burial would have required

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removal of much of the mud and because of profile restraints would have needed considerable excavation in rock outside the mud. The environmental effects and additional costs were not accepted. The steel shell is very much less stiff than the concrete in ring bending. While some load sharing would occur particularly as hinges form in the concrete, full composite behaviour was felt unreliable in the absence of shear connection between the two. Very large ships would not be expected to remain within Tolo harbour during a typhoon. Large carriers might manoeuvre in the area and could drop anchors despite the no-anchoring zone. The pipe was therefore designed to give the greatest practical resistance without thickening the concrete much beyond the limits normally required for effective submerged weight control. Up-to-date research indicated that the resistance would be greater than designed and in the unlikely event that severe damage occurred to the concrete, access was possible for repair and strengthening from the inside and grouting repairs would be possible externally.

59. Observations during construction confirmed that concern for behaviour in the mud was warranted. The most significant settlement was calculated to occur on flood-down and the pipe was able to cope without a bedding throughout the mud except at the interface with the hard soil. The sand bedding did not prevent the pipe from nosediving at the transition which illustrates the need for control at the nose which Mr Osorio has also described. Whereas large settlements may be acceptable structurally, they would not be acceptable if air pockets formed affecting fluid flow and pumping costs or for a sewer outfall where diffuser outlet levels need to be controlled within reasonable limits. Settlements on flood-down at Tolo were of additional concern because of the damage to the foundation during installation of the first line. Settlements were mitigated by placing an initial layer of fill before flooding in stages. Good communication, co-operation and care by all concerned contributed to successful completion of the work.

Reference

10. REYNOLDS J. M. and WILLIS D. A. Design and construction techniques for the future. In *Marine treatment of sewage and sludge*. Thomas Telford, London 1987, 258–281.