Executive Summary

Rationale for the study

The ability to predict local scour and its opposite, local deposition, is of critical importance to South Africa. Local scour can undermine bridge foundations (not just road/rail, but also pipe bridges) and riverbanks. Local deposition can clog river abstraction works used in the provision of water to rural communities and agriculture. Together, they impact aquatic environments and change the courses of rivers. Any structure placed in a river, whether of natural or of human origin, will tend to promote scour and deposition.

The failure of river crossings and engineering structures in rivers in South Africa due to scour damage can result in substantial financial and economic losses in flood-affected regions. For example, the well-known failure of the John Ross Bridge over the Tugela River during 1987 floods in Natal was caused by scour which undermined the bridge pier foundations (Van Bladeren & Burger, 1989). Vehicles which normally used the bridge had to travel significant additional distances. Such failures do not, however, occur in isolation as during these floods a total of 120 bridges in Natal were destroyed or severely damaged. As a consequence, substantial losses were felt by the local economy. Designing for scour is not, however, a mature science. There have been many developments since the publications of the South African National Roads Agency Ltd. *Road Drainage Manual* and the Committee of State Road Authorities (1986) and *Guidelines for the Hydraulic Design and Maintenance of River Crossings*, TRH 25 (1994). Furthermore, the mounting evidence for global climate change suggests that southern Africa must start preparing itself for the likely consequences of even more severe flood events and consequential damage to structures. There is also an increasing problem associated with scour and deposition around urban culverts / bridges – particularly as the modern tendency is to move away from concrete-lined channel sections towards more natural looking waterways.

The recently completed WRC study entitled *A unit stream power model for the prediction of local scour* (Armitage & McGahey, 2003) showed that there is still no universally agreed design procedure that can cope with all the observed scour and deposition phenomena. Most methodologies place considerable reliance on the use of dimensional analysis and empirical formulae and are extremely inaccurate. Physical models are more reliable, but are expensive. The road ahead ultimately lies with the use of computational fluid dynamics (CFD). A crude numerical model for the prediction of scour and deposition with the aid of CFD was developed in the course of the aforementioned WRC study.

The role of the engineering departments in many government institutions is changing from design to regulatory, and thus they are employing fewer and possibly less experienced engineers, and years of accumulated wisdom in design is gradually being lost. They have extremely limited funds for research. There is a pressing need for the development of appropriate tools to enable the designers of the future to make the optimal use of limited resources. These tools should include design guides for local conditions and the development of suitable software.

Objectives

The main objectives of this consultancy were as follows:

- Report on the extent to which local scour and deposition around culverts and bridges is a problem in South Africa.
- Conduct a literature review of the current state of the art regarding the CFD modelling of scour and deposition around manmade structures in the fluvial environment.
- Report on research needs with respect to the development of appropriate CFD tools for the prediction of scour and deposition around engineering structures.

Layout of this report

Chapter 2 offers a brief introduction to river scour in general, and local scour in particular. The mechanisms causing local scour around two simple structures – cylindrical piers and vertical plate abutments are also described.

Chapter 3 commences with a historical overview of scour damage to major river crossings in South Africa, and particularly Natal, over the past five decades. This is followed by a description of a field and desk study of 121 bridges currently experiencing scour problems. Analyses of the nature of the damage were conducted and estimates of the associated repair costs made. The study focused on scour at South African provincially maintained road bridges although pipe and rail bridges and other hydraulic structures were included to a lesser degree. Emphasis was placed on the assessment of scouring mechanisms such as general, local and constriction scour which attack bridge foundations directly. Erosion of earth embankment dams and berms was not considered.

Chapter 4 looks at numerical modelling of local scour in rivers through Computational Fluid Dynamics (CFD). CFD is the numerical modelling of fluid flow and associated phenomena (Versteeg & Malalasekera, 1995; Olsen, 1999). The fundamental equations and methods used by CFD are briefly described. Although there are many commercial and general-purpose CFD codes available, local scour is difficult to model owing to the three-dimensional nature of the vortices that are set up in the vicinity of hydraulic structures. This chapter describes previous work in the modelling of scour, and then illustrates the current capability of two well-known codes, FLUENT Version 6.2 (a general CFD code) and TELEMAC Version 5.4 (a specialised river modelling code).

Chapter 5 contains some general conclusions as well as providing recommendations for future research. It is followed by **References** and **Appendices**. The Appendices include cost estimates of current scour damage in South Africa, as well as giving details of commercial CFD codes (general and specialised river modelling codes) currently on the market.

Limitations of the study

It is important that the reader appreciates that local scour is but one type of scour. Scour, whether it be in the form of long-term bed degradation, constriction scour, bend scour, confluence scour or local scour, is a major engineering problem as all forms of scour have the potential to undermine hydraulic structures and potentially cause their collapse. This report focuses only on local scour; for the reason that it is one of the greatest threats to hydraulic structures whilst simultaneously being one of the most difficult to analyse as a result of the three-dimensional aspect of vortex formation and dissipation around these structures. Even in the context of a discussion of local scour, this report is still constrained. It deals only with two aspects: the extent of the problem in South Africa, and the state of the art of numerical modelling.

When dealing with the extent of the problem in South Africa, the focus is on provincially maintained road-over-river bridges. Other types of structure; e.g. pipe bridges, weirs, spillways, dikes, intake structures, canoe chutes, etc. are largely ignored. Even road bridges, bridges along National roads and roads maintained by local authorities are effectively ignored. Furthermore, estimates of local scour damage are restricted to repair costs with no attempt made to determine consequential costs e.g. delays or the additional maintenance and running costs associated with the temporary deviation of traffic.

In the discussion on the state of the art of numerical modelling, the report assumes the use of commercially available software running on desktop personal computers. Clearly a lot more can be done if the modelling is carried out on supercomputers or high-speed clusters of machines, but this option is not generally available for routine engineering work.

Ultimately the report is designed to give a snap-shot of the situation as it currently stands at the present from the perspective of technology that is readily available to all consulting engineers. It is clear, however, that the rapid improvements in the speed of personal computing and the associated rapid development of software will render this document dated within a relatively short period of time.

The extent of the problem in South Africa

Scour damage is generally associated with extreme flood events. A study of current scour damage at road bridges in South Africa has indicated that severe scour damage is seldom evident at bridges under "normal" flow conditions. Evidence of severe scouring during past floods was, however, seen at several sites. An estimate of the direct cost of repair of scour-related damage on provincially maintained bridges is approximately R22 million per annum. About 42% of this cost is on bridges in KwaZulu-Natal. This cost excludes the damage incurred in extreme flood events and the economic costs associated with the disruption caused by the failure of major transport links. Inclusion of scour damage during extreme floods events may increase the estimate to between R25 million and R30 million per annum.

The severity of the constriction scour observed in the field study was generally greater than the local scour. It might thus be said that excessive constriction of the flow poses a greater threat to South African river bridges. It must, however, be remembered that local scour cannot be readily observed or measured, particularly during extreme flood events, and the holes are rapidly filled by sediment after the peak flow has passed, which might lead to an underestimate of the impact of local scour. Furthermore, the two types of scour usually act in conjunction so one cannot be studied in the absence of the other.

Local and constriction scour are the two mechanisms occurring most frequently at bridge sites. Local scour was observed at 60% of the 105 bridges investigated whilst constriction scour was observed at 44% of them. The local and constriction scouring were combined at 37% of the sites investigated. The prediction and mitigation of local scour is thus an important area for research.

The state of the art of numerical modelling

The complex nature of real flow phenomena has historically made physical modelling attractive. However, the construction, modification, and operation of physical models can make them extremely expensive which is encouraging engineers to look toward numerical simulation using CFD either as an adjunct to, or as a replacement for, physical models. The main problems associated with CFD relate to the transfer of the underlying physics to the numerical solvers. This is made difficult because of complex interaction of many different factors coupled with the severe limitations in the computational power of the current generation of desk-top machines.

The first step in numerical analysis involves the identification and description of a suitable flow domain. The domain is then divided into finite volumes or finite elements by means of two or three-dimensional meshes. The choice of domain is extremely important. An adequate length of channel upstream and downstream of the structure must be modelled to ensure that any inadequacies in the boundary conditions have been smoothed out in the region of interest in the vicinity of the structure. In the case of relatively symmetrical flows around structures such as circular piers, the computational time can be greatly reduced by defining the line of symmetry and modelling only half the channel width – although this will obscure such physical phenomena such as the von Kárman vortex street. This analytical trick cannot, however, be applied to models around asymmetrical structures such as a spur dike. Finer meshes generally give a more accurate solution compared with coarser meshes, but they are computationally time intensive. Considerable skill is required to determine the optimum mesh size taking into account the computational time and model accuracy. At present, there are no generally agreed guidelines for mesh refinement – especially close to the structure, the river bed and the air-water (free-surface) interface.

The selection of the turbulence model is a key factor in numerical modelling. Each turbulence model has its advantages and disadvantages depending on the type and nature of the flow field to be modelled. The more accurate turbulence models such as Direct Numerical Simulation (DNS), Large Eddy Simulation (LES), Very Large Eddy Simulation (VLES), or Reynolds Averaged Navier-Stokes (RANS) improve accuracy (in decreasing order), but at an extremely high computational cost associated with the finer meshes and additional time steps required. As a consequence, the k-ε family of turbulence models are by far the most popular and extensively used for predicting the local scouring problems in spite of their well-documented limitations particularly in the separated zones.

Some commercially available CFD codes that could be used to solve scour problems are listed in Appendices B (General codes) and C (Specialised river codes). Trials using one example of each type of code; FLUENT – a general code – and TELEMAC – a specialized river code – quickly revealed major limitations with both. These were chosen on the basis of relatively low cost, good software support, and flexibility (they both allow for user-defined routines). FLUENT had an excellent user interface and great flexibility, but was not originally designed for open channel work, so features such as sediment transport and boundary adjustment had to be specially programmed into the code. The Volume of Fluid method was used to determine the position of the free surface, which was reasonably accurate, but computationally intensive. TELEMAC was designed for open channel work so there were already modules for sediment transport / boundary adjustment, but the three-dimensional module was effectively a multiple two-layer model which was too coarse to pick up some of the small scale vortices that are set up in the vicinity of structures. The default free surface routine assumed hydrostatic pressure variation – which is not the case in the vicinity of a structure. A major shortcoming of TELEMAC was that it had a poor user interface, whilst the documentation was out of date – or in French. Both models demonstrated limitations in the modelling of the velocity gradients (and hence all other parameters such as shear stress that are dependent on the velocity gradient) in the boundary layer near the water / solid interface – unfortunately the most critical area for scour modelling.

Recommendations for future research

The following recommendations are intended to guide further investigations into scour damage in South Africa and research into numerical scour prediction methods:

- Further investigation needs to be made into the extent of the scour damage around bridges resulting from major historical flood events with particular emphasis on the causes of failure, and the associated economic costs. These costs need to include consequential damages such as the cost of providing temporary services or the additional fuel, maintenance and time cost of travelling additional distances over detours. The investigation should focus particularly on KwaZulu-Natal as the costs associated with scour damage in this province are estimated to account for 42% of the total value of scour damage in South Africa. This is a consequence of KwaZulu-Natal having the highest average rainfall and largest number of bridges of the nine provinces.

- A more extensive review of the causes of failure of other hydraulic structures, e.g. intake structures, weirs and dikes, is necessary to give a better indication of the extent to which scour damage is a contributory factor.
- Local scour is a priority for further research as the severity of scour resulting from this mechanism under flood conditions is difficult to predict – or measure. Local scour was identified as the most prevalent form of scour damage observed at provincial road bridges during this study. More research into the combined effects of local and other forms of scouring should however be undertaken.
- A review of appropriate scour protection measures needs to be undertaken. This would have to be linked to the types of structures and environments found in South Africa.
- More research could also be undertaken into the impacts of deposition – particularly with regard to potential blocking of intake structures.
- Computing power is increasing very rapidly. This is leading in turn to a rapid improvement in the available software. Ongoing research is thus required to ensure that South African engineers keep pace with the development of suitable codes for the prediction of local scour and deposition that will, *inter alia*, enhance their capacity to design safe and durable hydraulic structures. Some aspects that require further attention include:
  - the optimum choice of incipient motion / sediment transport model in association with the appropriate numerical wall model for boundary adjustment
  - the impact of non-cohesive and/or non-uniform bed material
  - the impact of sediment load on flow properties (density, viscosity etc.)
  - live bed scour
  - rate of scour development
  - deposition
  - the potential use of discrete granular phase modelling as an alternative to empirical formulae (such as Van Rijn, 1987 etc.) to make the CFD

model more closely related to the physical processes and thus more generally applicable

- The possible linkages between high definition 3D hydrodynamic models and other types of models e.g. 2D river models, river ecology models etc. need to be explored. For example, 2D river models are ideally suited for the modelling of long river reaches where the flow is predominantly two dimensional. If these 2D models could be linked to a suitable 3D model, they would help to better describe the boundary conditions of the latter model – and thus its ability to predict scour and/or deposition. Meanwhile, ecologists have expressed great interest in modelling the hydraulic habitat of various organisms in an attempt to better understand how these affect the viability of these creatures.