CONCLUSIONS AND SUGGESTIONS FOR THE FUTURE WORK

Specific conclusions relating to the application of particle swarm optimization method and fish shoal optimization algorithm for the optimal design of earthen channels whose side slopes are riveted with riprap stones and bottom is unlined have been narrated in earlier chapters. However, generic conclusions related to the investigations on the optimal designs of riprap riveted earthen channels are given below under different subsections.

8.1 Application of Particle Swarm Optimization

The following conclusions are drawn out of the investigations into the optimal designs of riprap stone riveted earthen channels.

1. Particle Swarm Optimization method was found effective for designing the minimum cost riprap stone riveted earthen channels. A design procedure involving particle swarm optimization method could be established for the minimum cost riprap stone riveted earthen channels.
2. The present investigation involving different types of riprap stones, namely, round, subround and subangular, and angular for the design of channels whose side slopes are riveted with riprap stones and bottom is unlined reveals that the angular stone riveted channels offer the lowest cost relative to those of subround and subangular, and round coming next in sequence.
3. Emergence of the angular stone riveted channel as the best in cost terms alludes to the fact that the angularity of stone particles is a desirable attribute from the engineering utility perspective, which ensured a better

stability of angular stone particles on channels' side slopes. It also revealed the potential of angular stones to sustain a higher flow induced shear stresses, hence, the channels with angular stone revetment emerge out to be the best from the cost perspective.

4. The irregular shape of the angular stone particle offered it an additional interlocking capability to connect with other stone particles, which, in turn, causes the angular stone to remain stable on steeper side slopes of a channel. Thus, the irregular shape of the angular stone particle made it a better option for the revetment as compared to the other types of riprap stones.
5. Asymmetric shapes of the trapezoidal channels were adopted to facilitate more flexibility to the optimization algorithm to carry out search in 5-D Euclidean space but the results revealed that application of the same lot/bulk of the stones for banks' revetment caused the trapezoidal earthen channels riveted with different riprap stones to be symmetric in shape for cost effectiveness.
6. The capability of angular stones to remain stable on steeper side slopes further enabled the channels to acquire a relatively reduced cross sectional area with consequential higher flow velocity, thus, it makes the minimum cost channels to be the most hydraulically efficient as well. Therefore, it is appropriate to design a canal section having side slopes riveted with angular riprap stones for the minimum cost than to design for the maximum

hydraulic efficiency alone, since the minimum cost design formulation incorporating excavation, land acquisition, and riprap costs accounts for both the minimum cost and the hydraulic efficiency. This novel finding is of a huge relevance to the engineering domain.

7. The design of channels with sediment-laden flow condition near channel bottom adds another benefit for the optimization algorithm to reduce the construction cost even more by providing an additional flexibility as compared to the fixed value of the Manning's roughness coefficient under clear water flow condition near channel bottom.
8. As obvious, the freeboard provision was found to influence the cost of channel construction. The channels without freeboard have lower cost as compared to those having freeboard.
9. The channels are normally designed with a fixed magnitude of freeboard. The costs of channels with freeboard equation $f = 0.25 + 0.25\ y^{0.25}$ are found comparable with the one having fixed magnitude of freeboard. Therefore, the depth dependent freeboard equation $f = 0.25 + 0.25\ y^{0.25}$ is suggested for application, as it is appropriate to adopt a depth dependent freeboard than a fixed magnitude.
10. The channels having freeboard with round stone revetment were observed to be narrower than the channel without freeboard for both the clear water and sediment-laden flow conditions. However, the channels with sediment-

laden flow condition turned out to be relatively wider than those carrying clear water.

11. This finding revealed that the sediment-laden flow condition near channel bottom caused the optimization algorithm to achieve a wider channel. It happened because the optimization algorithm found an additional flexibility to choose channel specifications in such a manner that it reduced the value of Manning's roughness coefficient for the channel bottom. The reduction in the magnitude of Manning's roughness coefficient, coupled with the relatively higher cost of round stone, compared to the land cost, caused the channel to be wider for increased conveyance capacity and low cost.
12. Contrary to the round stones, the channels having freeboard with subround and subangular stone revetment were observed to be wider than the channel without freeboard for both the clear water and sediment-laden flow conditions. However, the channels with sediment-laden flow condition turned out to be relatively narrower than that carrying clear water. This indicates that the channels with subround and subangular stone revetment have achieved a relatively steeper side slopes and squeezed cross-section area. The optimization algorithm chose to have channel cross section narrower for sediment laden flow condition because the relative cost of land would have been higher than that required for revetment of steeper side slopes with subround and subangular stone. It is important to note that the

unit cost of subround and subangular stone is less than that of round stone.

13. Similar to the subround and subangular stone, the channels having freeboard with angular stone revetment were observed to be wider than the channel without freeboard for sediment-laden flow condition. For the case of clear water flow condition near channel bottom, it was found that the channels having freeboard with angular stone revetment possess the same shape for all the freeboard scenarios. It happened because the channels have achieved the least cross section area with the steepest side slopes and there was no further scope of improvement.

    However, the channels with sediment-laden flow condition turned out to be relatively narrower than that carrying clear water and this findings resembles with that of subround and subangular stone.

14. In conformity with the findings of Guo and Hughes (1984) for hydraulically efficient channel, the design of round stone riveted earthen channel thus becomes narrower for channels with freeboard but the same finding does not hold true for angular, and subangular and subround stones. Hence, their finding cannot be generalized as anticipated by the canal designers.

8.2 Application of Fish Shoal Optimization

In addition to the above findings, the following conclusions have been drawn from the application of fish shoal optimization algorithm to the problem of optimal channel design.

1. A novel methodology that can identify the most suitable type of the riprap stone for the design of the minimum cost earthen channel, whose side slopes are riveted with loose riprap and bottom is unlined, is developed. The method is referred to as Fish Shoal Optimization algorithm to portray its resemblance with the biological character of a fish shoal (aggregation of mixed species of fish) in nature.
2. The Fish Shoal Optimization algorithm accommodated different types of riprap stones together to generate a population of mixed species to imitate the social characteristics of a fish shoal. The dissimilar members of a shoal socially interact-a characteristic of Particle Swarm Optimization method, and compete-a feature of Genetic Algorithms, with their own subgroup and other subgroup species to capture the leadership role to steer the movement of shoal for finding the global optima in search space. Thus, it added an additional novelty in the present work.
3. Fish Shoal Optimization algorithm can compare the performances of the different subgroups, hence it finds application in wide varieties of fields. However, it needed an additional dimensional space (5-D for actual

problem+1 for subgroup characterization) to characterise the subgroups involved in the optimization problem.

4. In order to compare the performances of different subgroups, Fish Shoal Optimization algorithm requires its objective function to be defined in a typical manner so that it can yield the cost functions (3 for the present study) for different subgroups involved in the optimization problem.
5. The Fish Shoal Optimization algorithm offered the solution comprising canal bottom width, side slopes, flow depth, stable riprap stone size, and the most suitable type of the stone for revetment of canal side slopes which was not been investigated earlier by involving different types of riprap stones into a single computational program for optimal canal design.
6. The Fish Shoal Optimization algorithm required only one set of penalty parameters, which eliminated the need of different sets of penalty parameters for each type of riprap stone when particle swarm optimization method was applied.
7. It is interesting to note that the Fish Shoal Optimization algorithm offered the better solutions than those obtained by the applications of particle swarm optimization method. This happened because of the stiff competition that prevailed during optimization process among the different subgroup members. Thus, the efficacy of Fish Shoal Optimization algorithm in terms of yielding the minimum cost channel was observed to be better than particle swarm optimization method.

8.3 Suggestions for the Future Work

The present investigation involving the application of particle swarm optimization and fish shoal optimization algorithm considered an earthen channel whose side slopes were riveted with the three different types of riprap stones and bottom was unlined. The example problem was adopted from the literature to compare the results with those of published data. However, the proposed methodology can be applied to any field problem relating to the optimal design of canals. Since the comprehensive cost data could not be found from a canal construction site in Indian, the cost data were obtained from a real canal construction site in Arizona, USA. However, the data related to the cost of items for canal construction can be obtained from a case study relating to the Indian context. Further, the data related to the cost of riprap stones were observed to vary significantly from one country to the other; therefore, a fuzzy membership function can be used for the cost of riprap stones. The application of the fuzzy membership function for the cost of riprap stones would have resulted in the several other design options. The optimal designs were obtained for the deterministic values of known parameters but a probabilistic analysis can also be carried out to get more realistic solutions. The uncertainties related to the decision variables can also be included in the study. Further, the freeboard scenarios were generated to match the real cases, however, some more scenarios can be generated to obtain additional solutions. The novel optimization algorithm can also be applied to some more problems to validate its efficacy and robustness.